Indigenous Archaeological Fisheries Records Provide Evidence of Multiple Baselines in the Northeast Pacific

By

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We acknowledge and respect the lək̓ʷəŋən peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

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Abstract

It is well recognized that humans have had a significant role in transforming terrestrial landscapes, yet comparatively little research has examined the long-term impacts of humans on marine ecosystems. As an applied field of research, marine historical ecology draws on archaeological, ecological, and other archival information to reveal the dynamics of marine social-ecological systems. This thesis examines the enduring history of relationships between ancient Indigenous fisheries and marine systems in the northeast Pacific. Specifically, I advance the development and application of two methodologies for 1) quantifying the composition of ancient fish landings, 2) estimating ancient ocean temperatures from archaeological fish bone assemblages, and 3) assessing the scale of ancient shellfish harvests using a regression-based approach. This thesis presents a novel method for estimating the 'ancient Mean Temperature of the Catch' (aMTC) using Indigenous fisheries catch records from two archaeological sites in the northeast Pacific. Despite different catch compositions, I observe an increase in aMTC over a 5,000-year period at two contemporaneously occupied archaeological sites in southwestern British Columbia, Canada. Given that preindustrial fisheries data are ubiquitous in coastal archaeological sites, this method has the potential to be applied globally to broaden the temporal and geographic scale of ocean temperature baselines. Furthermore, the regression-based methodology presented in this thesis has broad applicability to archaeological shellfish assemblages, as it allows for reconstructing size frequency distributions of ancient shellfish harvests and refined estimates of clam biomass. Together, these methods offer a long-term perspective on the enduring relationships between Indigenous peoples and marine environments in the northeast Pacific. Furthermore, the methods advanced in this thesis shed light on ancient oceanographic conditions and fisheries practices, which can be used to inform contemporary management efforts. Ultimately, these insights aim to contribute towards ecologically sustainable and socially just operating space for Canada’s Pacific fisheries.

Table of Contents

List of Tables

List of Figures

Preface

Chapter 2 is written as a co-authored manuscript that has been submitted to the journal *Environmental Biology of Fishes*. Significant contributions have been made from Robert Gustas (University of Victoria) and Daniel Pauly (University of British Columbia), as well as William Cheung, Anne Salomon, and Iain McKechnie.

Chapter 3 is written as a co-authored manuscript to be submitted to a peer-reviewed journal. Substantial knowledge contributions and editing have been made from Erin Foster (University of Victoria), Anne Salomon, and Iain McKechnie.

Due to this structure, there is minor redundancy between chapters.

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Dedication

This thesis is made in honour of the generations of fishers who come before us.

Chapter 1: Introduction

1.1 Thesis Introduction

Globally, fisheries have supported human life and well-being for millennia. Providing an important source of nutrition, fish, shellfish, and other marine organisms have served an essential role in human food systems since the Pleistocene (Erlandson 1988; Klein et al. 2004; Marean et al. 2007; O’Connor et al. 2011; Stringer et al. 2008). Archaeological evidence suggests that aquatic and maritime adaptations factored prominently in the expansion of humans after ca. 150,000 years ago (Erlandson 2001). While archaeological evidence of fishing in the Pleistocene is difficult to detect (Erlandson 2001; Klein et al. 2004; Marean et al. 2007; O’Connor et al. 2011), largely due to changing sea levels and the subsequent erosion of coastal sites, the importance and antiquity of marine resources for supporting human well-being must not be overlooked. Yet, many archaeologists have only recently began to recognize that humans were capable of influencing marine ecosystems in the deep past (Erlandson and Rick 2010). This paradigm followed the belief that the oceans were either inaccessible to early humans, or inexhaustible using ancient fishing technologies.

Today, nearly all the world’s fisheries have experienced significant declines due to a wide range of anthropogenic impacts (Steneck and Pauly 2019). The decline in fisheries globally has often been attributed to technological innovations, the emergence of global markets, and exponential human population growth (Erlandson and Rick 2010). Yet, as Jackson et al. (2001) note, the effects of overfishing throughout the 20th century has preceded all other forms of anthropogenic impacts in the ocean. While few question the role these factors have had on marine ecosystems, this colonial worldview has also served to minimize our understanding of how ancient peoples shaped the composition and structure of ecological communities in the deep past.

While human involvement in marine systems has ancient roots, contemporary fisheries management decisions often lack a deep-time perspective on oceanographic variability. Until recently, marine ecologists have tended to view coastal habitats as ‘natural’ or ‘pristine’ communities from which to measure ecosystem change (Jackson 2001). Such a perspective is fundamentally flawed, as it ignores the role of pre-industrial fisheries in shaping marine systems and thus, the potential for multiple baselines. As Pauly (1995) notes, the ‘shifting baseline syndrome’ has been responsible for masking the true extent of stock declines and ensuing ecological restructuring, as each generation of fisheries scientists are unable to remember previous baselines. In other words, with each successive generation of managers identifying their contemporary (albeit depleted) environment as a pristine natural baseline, previous – more abundant and ecologically diverse – conditions are forgotten.

While contemporary fisheries management decisions are often limited to decadal scale climatic records and industrial-era fisheries baselines (Steneck and Pauly 2019), anthropological, archaeological, and palaeoecological data have the potential to broaden perspectives and identify changes beyond the past half-century (Jackson 2001; Jackson et al. 2001). In southern California, for example, marine sediment cores have been used to show periodic and cyclical shifts in the abundance of Pacific sardine (*Sardinops sagax*) and northern anchovy (*Engraulis mordax*) populations over the past 1,850 years (Baumgartner 1992; Soutar and Isaacs 1969), which are associated with warmer and cooler ocean temperatures, respectively. Furthermore, Chavez et al. (2003) document synchronous variations in Pacific sardine landings across the Pacific (i.e., California, Chile, Japan, and Peru) over the past century. In coastal British Columbia (BC), marine sediment cores from Saanich Inlet and Effingham Inlet reveal shifts in the abundance of fish remains preserved in laminated sediments (O'Connell and Tunnicliffe 2001; Tunnicliffe et al. 2001; Wright et al. 2005). Notably, these studies document periods of increased primary productivity at 6,500 and 1,500 years before present (BP). Collectively, these multiple lines of evidence offer a deep-time perspective on oceanographic variability. Estimating long-term climatic baselines is an essential step for understanding magnitudes of change, which can be used to inform recovery targets and build resilient fisheries.

In the northeast Pacific, marine fisheries have existed as a fundamental component of Indigenous communities for more than ten millennia (Brown et al. 2009; Fedje et al. 2005; McKechnie and Moss 2016; Moss 2011). This reality is recognized in Indigenous philosophies and legal orders (Todd 2018), and more recently in Indigenous peoples' constitutional right to fish (R.S.C. 1985). Indigenous oral histories, ethnographic accounts, and archaeological evidence document an enduring and vital role for fish in supporting livelihoods, as well as providing a source of nutrition, trade, and cultural identity for coastal Indigenous peoples (Moss 2011; Moss 2012; Moss and Cannon 2011). For coastal First Nations in BC, fishing represents more than simply the act of provisioning ‘food’ or ‘resources,’ rather it is more accurately conceptualized as framework of relations between human and non-human persons (Atleo 2004; Brown et al. 2009; Claxton and Elliott 1994; Todd 2018).

Throughout coastal BC, the enduring role of fisheries are documented in extensive shell-bearing sediments (i.e., shell middens) that are superabundant in fish bones and marine shells. Fish bones account for the greatest proportion of faunal remains in zooarchaeological assemblages (Moss and Cannon 2011), of which Pacific herring (*Clupea pallasii*) and salmon (*Oncorhynchus* spp.) are proportionally the most abundant and ubiquitous (McKechnie and Moss

2016). These multiple lines of evidence document the fundamental role of local fisheries in supporting the social- and economic-wellbeing of coastal Indigenous peoples in the northeast Pacific, over millennia. However, declines in fish stocks throughout the 20th century and more recent climate induced effects present a serious threat to community fisheries today.

Recent research has established that warming of the oceans is affecting the distribution, abundance, and productivity of fish populations globally (Cheung et al. 2013; Duarte et al. 2020; McClenachan et al. 2019; Pinsky et al. 2013; Poertner and Knust 2007) and is projected to severely erode the social and economic well-being of coastal communities (Golden et al. 2016; Weatherdon et al. 2016; Wilson et al. 2020). Considering that many essential nutrients are found only in animals, it is estimated that 1.39 billion people globally (19% of the current global population) are vulnerable to malnutrition due to declining fish populations (Golden et al. 2016; Maire et al. 2021). In BC, current projections indicate that many local fisheries are expected to decline (Weatherdon et al. 2016), which presents serious risk to the food and economic security of coastal Indigenous communities. Fisheries managers can benefit from considering the effects of climate change on marine fisheries in the deep past, which will better inform contemporary management practices.

This thesis examines the enduring legacy of Indigenous fisheries in coastal BC through the framework of marine historical ecology. As an interdisciplinary field of inquiry, marine historical ecology seeks to understand ancient interactions between people and environments (Balée 1998; Balée 2006; Beller et al. 2017; Crumley 1994). In this thesis, I draw upon multiple lines of evidence to gain insight into the reciprocal relationships between ancient Indigenous fishers and marine systems, over the past five millennia. Specifically, this research advances the development and application of the ‘Palaeothermometer’ approach for estimating long-term oceanographic conditions. Additionally, I develop and present a regression-based methodology to estimate the size of archaeological clam shells, using modern measurement data. Collectively, these methods aim to inform fisheries management decisions today by extending climatic baselines and catch records into the deep past to show how Indigenous fisheries responded to changes in the structure of marine systems. The novel methods presented in this thesis highlight the enduring role of Indigenous fisheries in the northeast Pacific, while also contributing towards fostering ecologically sustainable and socially just operating space for Canada's Pacific fisheries.

Position and Aspirations

I would like to acknowledge with respect the privilege it has been to work and study in the Indigenous lands of the Esquimalt, Lekwungen, Songhees, and W̲SÁNEĆ peoples. I was born and raised on Salt Spring Island (BC) and grew up amongst the southern Gulf Islands – lands that reside within the traditional and unceeded territories of Coast Salish peoples. As a descendent of settler-colonials, my family has resided in BC for four generations and has primarily engaged in the forestry and fishing industries. My family's connection to the commercial fishing industry in BC and my own experience working as a deckhand on my father's fishboat has been instrumental in fostering my sense of place and identities. Ultimately, this heritage motivates my interest in marine historical ecology and fisheries management.

As a person of European descent, I recognize that I have benefited from the same colonial government that drastically and intentionally impacted Indigenous peoples' relationships with marine systems. As a descendent of a fishing family and an archaeologist, I strive to use my privileged position to right the injustices imposed by colonial powers and repair relationships (Asch 2002; Harris 2004; Harris 2009) by celebrating the rich heritage of the territories on which I live and work. Accordingly, this thesis is motivated by the following aspirations:

- To emphasize the rich history of relationships between humans and marine systems in the northeast Pacific.
- To examine the resilience of Indigenous fisheries in the deep past.
- To resituate and redefine the role of zooarchaeological data in contemporary fisheries management practices.

Outline

In Chapter 1, I provide an introduction and overview of archaeological fisheries research and the current state of global fisheries. Chapter 2 and Chapter 3 exist as two independent research projects that offer novel methodologies for assessing the resilience of ancient indigenous fisheries. Specifically, Chapter 2 presents the ‘Palaeothermometer’ approach for estimating long-term oceanographic conditions using zooarchaeological ‘bone counts’ recovered from two Indigenous settlement sites in Barkley Sound, western Vancouver Island, BC. Chapter 3 develops a regression-based method for estimating the size of archaeological clam shell assemblages using measurements of modern clams collected from various locations in coastal BC. Finally, Chapter 4 offers a synthesis of the two methodologies presented here and explores the resilience of ancient Indigenous fisheries to climate change and human harvest pressure.

1.2 Research Questions and Methods

This thesis is driven by two research questions that aim to better understand the resilience of ancient Indigenous fisheries in coastal BC. Each question is briefly described below, with substantial background information presented in the literature review. The following two questions serve as the guiding framework for Chapter 2 and Chapter 3.

In coastal BC, fisheries management decisions are reliant upon recent climate records and fisheries baselines that encompass decadal scale timelines (Steneck and Pauly 2019). This presents a major challenge for assessing long-term climatic baselines and understanding magnitudes of change, which are essential for informing recovery targets and building resilient fisheries. Currently, fisheries managers in coastal BC rely on relatively short-term quantitative estimates to evaluate changes in harvested biomass and do not account for early commercial fishery removals or past oceanographic variability. Zooarchaeological insights have the potential to provide a deep-time perspective on oceanographic variability and ancient harvests. Drawing on archaeological data, this research develops novel methods for 1) quantifying the composition of ancient fish catches, 2) assessing long-term oceanographic variability, and 3) estimating shellfish biomass from ancient Indigenous harvests.

Questions 1 & 2: ***How can zooarchaeological fisheries data be used to generate estimates of fish and shellfish biomass? What are the steps and sources of uncertainty in generating biomass estimates?***

Archaeological fisheries data can provide insight into long-term variability in oceanographic conditions and ancient fish catches, which can be used to inform conservation targets that foster social and ecological well-being (Kittinger et al. 2015; Lotze and McClenachan 2013; McClenachan et al. 2012). While archaeological sites in the northeast Pacific are dominated by fish and shellfish remains, quantitative zooarchaeological investigations into the scale of past fisheries landings (i.e., harvested biomass) in the region are currently nonexistent. Furthermore, the use of zooarchaeological fisheries data for understanding ancient oceanographic conditions represents a novel methodological approach that has yet to be applied to an archaeological context.

In Chapter 2, I present a novel method for estimating the composition of fish landings from ‘bone counts’ of archaeological fish remains for an area in coastal BC. Drawing upon the

‘Minimum Number of Individuals’ (MNI), I am able to quantify the relative proportion of the catch (% biomass) by multiplying MNI by the body mass for each taxonomic category of fish. Following this, I apply ‘Mean Temperature of the Catch’ (MTC) calculations (Cheung et al. 2013) to estimates of fish biomass generated from archaeological data at two settlement sites on western Vancouver Island, BC. Considering that coastal archaeological sites with fisheries records are present across the globe, this research methodology illuminates the potential for detecting shifts in fisheries from myriad locations and timescales.

In Chapter 3, I develop a regression-based method for assessing the size distribution of ancient shellfish harvests using a range of modern shellfish samples. As archaeologically recovered shellfish remains are often fragmentary, researchers require new methods for quantifying the scale of past shellfish aquaculture practices. Despite the ubiquity of coastal archaeological sites in the northeast Pacific, which are often comprised of significant amounts of shellfish remains, little work has been done on calculating the total biomass represented within and across sites. Drawing upon modern measurement data to inform linear regression models, I present a method for assessing size frequency distribution profiles for economically valuable shellfish. By converting size distribution profiles into estimates of biomass (i.e., total clam weight and wet meat weight), future researchers can scale up analyses to understand potential shifts in shellfish biomass over time. Importantly, the methods presented in Chapter 3 represent a first step in generating estimates of ancient Indigenous shellfish harvests.

1.3 Background and Literature Review

Historical Ecology

As an interdisciplinary research program, historical ecology seeks to understand the spatial and temporal dimensions of human life. More specifically, historical ecologists are interested in human relationships with local environments and the cumulative effects of these relationships (Balée 2006). Ingold (1993) describes the landscape as an enduring record of the “lives and works of past generations who have dwelt within it, and in so doing, have left there something of themselves.” In this way, human-environment interactions have influenced the composition and evolution of ecological systems, thus creating a dynamic feedback relationship between biological and cultural systems (Fuentes 2016).

Human-environment interactions have the potential to result in significant alterations to biodiversity distributions and the radical reconfiguration of ecological systems (Boivin et al. 2016; Zeder 2018). Over time, the cumulative effects of human activities can lead to dramatic environmental changes with long-term consequences. In the current context of the Anthropocene, people must now reconcile with human-dominated landscapes (and seascapes), characterised by extensive anthropogenic effects and climatic variability (Brewer and Riede 2018). Due to these cumulative effects, humans are now required to address and adaptively respond to the long-term consequences of past decisions. In so doing, humans can incorporate and foster resilience into adaptive management strategies.

Archaeology is a powerful mechanism for identifying evidence of human activity in the distant past and can inform researchers of ancient practices that may have resulted in the reconfiguration of ecological systems. The perspective archaeology provides (i.e., centennial to millennial timescales) is essential for understanding human-environment interactions, as archaeological sites document a wide range of human activities that occurred under various climatic and ecological conditions (Hambrecht et al. 2018). As an anthropogenic feature, archaeological deposits are fundamentally selective archives of ancient conditions. Despite this limitation, archaeological deposits can shed light on past ecological and climatic baselines

(Orchard and Clark 2005; Sandweiss 2003). In the marine environment, faunal remains recovered from archaeological assemblages have been used to provide valuable information for understanding the scale of human resource use in the past (Fossile et al. 2019; Jackson et al. 2001; McKechnie et al. 2014).

Despite the general lack of attention given to zooarchaeological data, other investigations into ancient oceanographic conditions and climatic variability have been a productive field of inquiry. For example, by isotopically analyzing sediment cores from southwestern Yukon, Anderson et al. (2007) documented changes in the circulation pattern of the Aleutian Low pressure system over the Gulf of Alaska throughout the late-Holocene. On Kodiak Island, Alaska, Finney et al. (2002) examined changes in sockeye salmon abundance in sediment cores to demonstrate large-scale oceanographic regime shifts, which occurred between 1,200-800 yr BP. The oceanographic transition occurring at 1,200 yr BP in the Gulf of Alaska is also documented by Orchard and Clark (2005), Maschner et al. (2009), McKechnie (2012), and Praetorius et al. (2015). Ultimately, these broad scale climatically related changes provide insight into past oceanographic conditions.

Globally, fisheries are experiencing shifts in the distribution and composition of fish populations, largely in response to anthropogenic climate change (Cheung et al. 2013; Pinsky et al. 2013). In the northeast Pacific, climate change will significantly impact fisheries catch potential, which presents a serious threat to coastal communities (Weatherdon et al. 2016). Because marine fish track local temperatures closely, ocean warming is expected to shift fish populations to higher latitudes and deeper waters (i.e., the ‘tropicalization’ of the catch) (Cheung et al. 2013).

Fisheries researchers have developed a method for calculating the ‘Mean Temperature of the Catch’ (MTC) and have used this metric to detect widespread marine climate trajectories for mid-latitude oceans, globally (Cheung et al. 2013). MTC is an index representing the preferred temperature range for specific species of fish and can be used to evaluate the potential effects of climate change on local fish populations based on catch data (ibid.). By calculating MTC as the average inferred temperature preference for harvested species weighted by their annual catch, Cheung et al. were able to attribute changes in MTC to ocean warming. Utilizing the MTC method, this study documented a shift in global fish populations to higher latitudes over a 36-year period.

As fisheries become increasingly dominated by warmer water species, coastal communities are presented with serious challenges which threaten local food security, as community fisheries will see reductions in catch potential for valuable food fish (Golden et al. 2016; Weatherdon et al. 2016). Assessing the potential impacts of climate change on fish populations is essential for informing First Nation fisheries management strategies, which can be used to structure resilience into local fishing practices. Furthermore, quantitative investigations into the scale of past fish and shellfish landings are urgently required to better understand the role Indigenous ancestors had in shaping marine social-ecological systems in the northeast Pacific.

Resilience Theory

Fostering the resilience of social-ecological systems is critical for supporting human well-being (Biggs et al. 2012). Originally forwarded by Holling (1973), resilience theory exists as a research framework that has been adopted by many disciplines and diverse actors with the aim to describe the dynamic nature of social-ecological systems. It follows that ecological and social systems are able to respond and adapt to perturbations over time; yet, crossing a critical threshold can trigger catastrophic change and reorganization into a new stable state (Angeler et al. 2016). Walker et al. (2004) note, “Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks.” As a research framework, resilience scholarship has the potential to inform managers in ways that can enhance or erode resilience to foster social-ecological wellbeing.

In contemporary resilience scholarship, the term resilience is used as a measure for assessing system dynamics and can be broken down into three core elements: process, rate, and emergent property (Allen et al. 2019). Resilience as a process is best conceptualised within the disaster response and development communities. Often, actions can be taken to enhance the resilience of specific aspects of social-ecological systems in response to natural disturbances, such as earthquakes and floods. In the northeast Pacific, sea otters (*Enhydra lutris*) exist as keystone species that can shape the composition of ecological communities and thus, represent a natural form of disturbance in marine systems (Foster 2021; Foster et al. 2021; Gregr et al. 2020; Kvitek et al. 1992; Markel and Shurin 2015; Singh et al. 2013). The ability for social-ecological systems to re-organize and learn in response to disturbances underscores resilience as a process, rather than a fixed state of being.

Resilience as a rate refers to the recovery of a system in response to a disturbance (Allen et al. 2019; Walker et al. 2004). In fact, a useful application of measuring resilience as a rate can help assess how long it takes for a system to recover following a disturbance. This understanding of resilience as a rate presents a fruitful intersection with the field of historical ecology, as the concept of shifting baselines can provide historical context for the various stable states systems occupied in the past.

Resilience as an emergent property refers to the potential of a system to occupy alternative stable states. Allen et al. (2019) recognizes that “alternative states are ‘stable’ due to feedbacks that arise from interactions between abiotic and biotic factors.” Yet, when a disturbance threshold is surpassed systems can fundamentally reorganize into an alternative stable state. This understanding of resilience as an emergent property embraces complexity and accounts for multiple feedbacks operating at different scales, which is critical for understanding social-ecological systems.

The three core elements of resilience provide a framework for quantifying the adaptive capacity of social-ecological systems to change. The intersection between resilience scholarship and historical ecology presents an opportunity to better understand social-ecological systems in the deep past. Specifically, how Indigenous ancestors interacted with and shaped marine communities, and importantly, how these constellations of relations acted back on human systems.

As with any field of scientific inquiry, resilience scholarship draws upon a host of terminology and associated concepts to help actors conceptualize their systems. Since the explosion of resilience scholarship in the early 2000s, there has been numerous competing frameworks, approaches, and terminology that serve to limit our understanding of how to navigate change (Walker et al. 2004). The following list of definitions are provided to reconcile the various terms used in resilience scholarship today, while relating back to the core themes presented in this thesis.

As originally defined by Holling (1973), ecological resilience refers to the amount of disturbance required to change an ecosystem from one set of processes and structures to another. The concept of engineering resilience focuses on the structural and functional elements of systems, specifically, how systems return to pre-disturbance conditions (Allen et al. 2019). In this way, the time it takes for a system to recover (i.e., return time or bounce back) becomes the unit of measurement. The term resiliency is analogous to engineering resilience and "refers explicitly to the capacity of a system to return to its initial state following disturbance" (Angeler et al. 2016). Adaptative capacity refers to the ability of a system to change and adapt in response to a future stressor. While resiliency and engineering resilience feature prominently in environmental management contexts, these terms assume that systems are characterized by a single equilibrium which ignore the potential for alternative states.

Throughout human history, people have shaped environments in ways that have, in turn, reconfigured social systems through a dynamic process of co-evolution (Berkes et al. 2000; Norgaard 2006). In this way, human societies and 'natural' environments have become deeply intwined. This understanding has led to the recognition of these co-evolutionary relationships as complex adaptive social-ecological systems (Folke et al. 2002).

Complex adaptive social-ecological systems thinking is an effective framework for understanding long-term change and can guide sustainability efforts. As a fundamental element of social-ecological systems, the adaptive cycle describes the dynamics of such systems that result from the "internal process of self-organization and evolution over time" (Sundstrom and Allen 2019). Feedbacks are a central aspect of the adaptive cycle and stem from the interactions between processes, structures, and species compositions. Sundstorm and Allen (2019) go on to note, at its core the adaptive cycle is defined by "system potential, connectedness, and resilience." In other words, potential refers to the range of possible options, connectedness is a measure of flexibility or rigidity in a system, while resilience is a measure of vulnerability to shock (Holling and Gunderson 2002). Furthermore, panarchy can be understood as a series of nested adaptive cycles operating at different scales within the same social-ecological system. Importantly, interactions are not static but rather operate asymmetrically across the panarchy model (i.e., large and slow vs. small and fast; Figure 1).

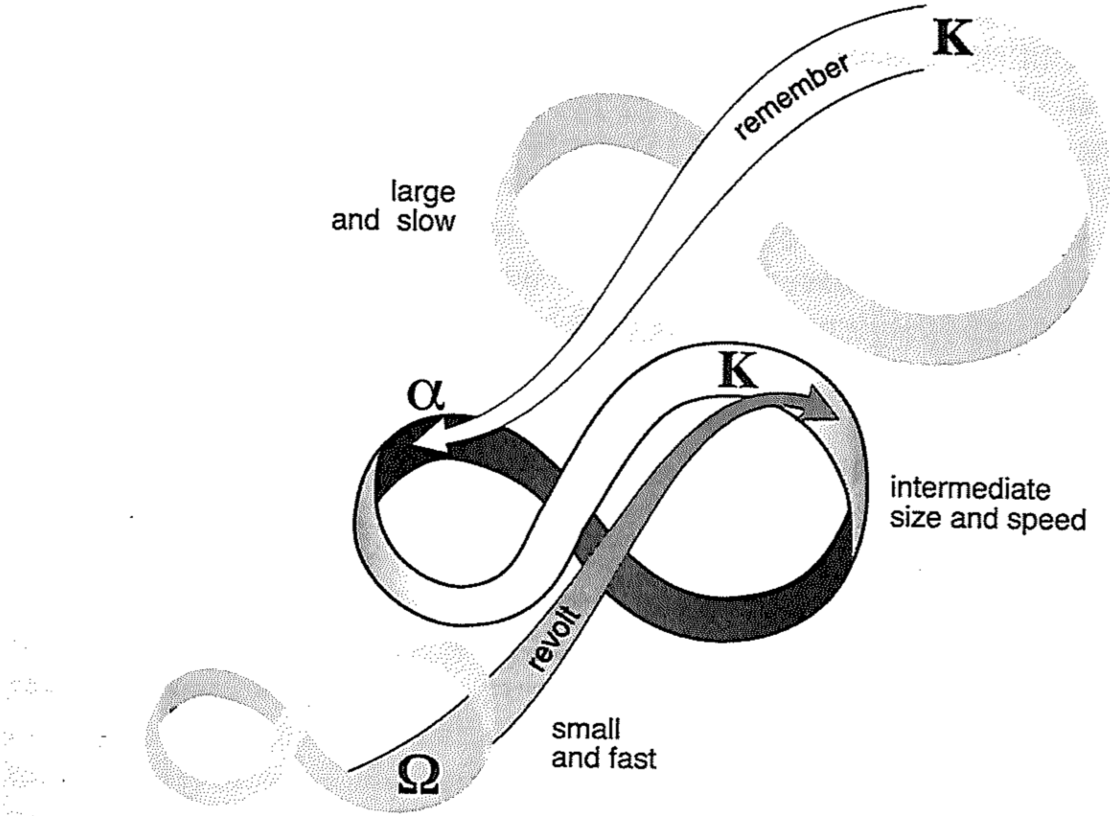

Figure 1 The panarchy model presents a series of nested adaptive cycles that operate across scales and are critical for creating and sustaining adaptive capacity. At the small and fast level, change can cascade up thereby influencing the large and slow level. At the large and slow level, the ability for systems to 'remember' connections can facilitate renewal by drawing on the potential of systems accumulated and preserved in the large and slow cycle. Figure originally presented in Holling and Gunderson (2002).

Such an understanding of the complexities associated with social-ecological systems is imperative for recognizing adaptive practices and activities that fostered resilience in the deep past, which can inform sustainable futures. As Salomon et al. (2019) state, “Quantifying how multiple dimensions of social-ecological resilience have changed through time can reveal strategic opportunities and leverage points to help guide governance transformation toward a more desired, resilient, and socially just system.” In the following chapters, I explore how Indigenous ancestors in coastal BC fostered resilience and adaptive capacity into their local fisheries, and how these social-ecological systems responded to disturbances in the form of climatic variability, human harvesting pressure, and predatory sea otters. The value of this approach is in its ability to extend historic baselines into the deep past, which will provide fisheries managers with a long-term perspective on the resilience of coastal Indigenous fisheries.

Chapter 2: A Palaeothermometer of Ancient Indigenous Fisheries Reveals Increases in Mean Temperature of the Catch Over Five Millennia

2.1 Abstract

Climate change is altering the distribution and composition of marine fish populations globally, which presents substantial risks to the social and economic well-being of humanity. While deriving long-term climatic baselines is an essential step for detecting and attributing the magnitude of climate change and its impacts, these baselines tend to be limited to historical datasets and palaeoecological sediment records. Here, we develop a method for estimating the ‘ancient Mean Temperature of the Catch’ (aMTC) using Indigenous fisheries catch records from two archaeological sites in the northeast Pacific. Despite different catch compositions, we observe an increase in aMTC over a 5,000-year period at two contemporaneously occupied archaeological sites in southwestern British Columbia, Canada. We document cooler catches from 5,000-3,000 cal yr BP and comparatively warmer catches during 1,800-250 cal yr BP. These warmer temperatures are broadly consistent with palaeoceanographic sea surface temperature proxies from British Columbia and Alaska. Because this method requires converting measures of fish bones into estimates of fish size structure, abundance, biomass, and finally aMTC, opportunities exist to account for both variation and uncertainty at every step. Nevertheless, given that preindustrial fisheries data are ubiquitous in coastal archaeological sites, this method has the potential to be applied globally to broaden the temporal and geographic scale of ocean temperature baselines.

2.2 Introduction

Warming of the oceans is affecting the distribution, abundance, and productivity of fish populations globally (Cheung et al. 2013; Duarte et al. 2020; Pinsky et al. 2013) and is projected to severely erode the social and economic well-being of coastal communities (Golden et al. 2016; Weatherdon et al. 2016; Wilson et al. 2020). In the northeast Pacific, marine fisheries have supported Indigenous communities for millennia (Brown et al. 2009; McKechnie and Moss 2016; Menzies 2006), a reality that is recognized in Indigenous peoples' constitutional right to fish for food, social and ceremonial purposes (R.S.C. 1985). As an economic mainstay and source of nutrition and cultural identity, fisheries have existed as a fundamental component of Indigenous communities in British Columbia (BC) throughout the Holocene (Fedje et al. 2005; Moss and Cannon 2011). Indigenous oral histories, ethnographic accounts, and archaeological evidence document the sustained use of a wide range of coastal resources throughout the region where assemblages are often numerically dominated by marine fish bones and shellfish remains (Moss 2012). By an overwhelming margin, fish account for the greatest proportion of vertebrate remains (i.e., identified bone fragments), and Pacific herring (*Clupea pallasii*) and salmon (*Oncorhynchus* spp.) tend to be the most abundant and ubiquitous (McKechnie and Moss 2016; Moss and Cannon 2011). While this evidence indicates an enduring and important role for fisheries in the northeast Pacific, there is no consensus on how zooarchaeological 'bone counts' can be translated into estimates of fish abundance, size structure, or biomass.

Currently, most fisheries management decisions rely on data spanning the past several decades to inform present and future population dynamics (Kittinger et al. 2015; McClenachan et al. 2012). Such an approach to fisheries management is fundamentally limited, as modern data lack a deep-time perspective on the history of human fisheries (Steneck and Pauly 2019).

Zooarchaeological fisheries data have the potential to provide millennial-scale time series that can reveal long-term variability in oceanographic conditions and ancient catch portfolios. Here, we develop a method based on zooarchaeological analyses of fine screened fish remains from two Indigenous archaeological sites in coastal BC to estimate relative proportions of fish biomass and ultimately past ocean temperatures, over the past five millennia.

In this chapter, we apply the ‘Mean Temperature of the Catch’ (MTC) concept, developed to analyze responses of contemporary fisheries catches to changes in ocean temperature (Cheung et al. 2013), to estimates of fish biomass to back-cast long-term trajectories in past ocean temperatures in the northeast Pacific. Our data indicate that coastal Indigenous fisheries catches reflect cooler ocean temperatures between ca. 5,000-3,000 years ago compared to ca. 1,800-250 years ago, both of which are cooler than modern bottom trawl catches. Despite differences in the composition of fish catches between archaeological sites, we observe consistent patterns of increasing MTC. These findings parallel observations from palaeoecological sediment records, indicating long-term ocean warming since the mid-Holocene. Given this is the first estimate of this kind, we highlight the analytical steps and sources of uncertainty in generating temperature estimates, in addition to the opportunities and challenges in applying the Palaeothermometer approach to other archaeological settings and time periods. As coastal archaeological sites with zooarchaeological fisheries data are globally distributed, the method advanced here has the potential to be applied elsewhere. We argue that the Palaeothermometer approach can provide a deep-time perspective on oceanographic variability, the composition of ancient fish catches, and magnitudes of change in the abundance and distribution of fish populations.

2.3 Materials and Methods

Fisheries researchers have established that fish species exhibit and maintain through time a preferred temperature range and have subsequently developed methods for detecting shifts in the composition of fisheries as they relate to ocean climate trajectories (Cheung et al. 2013; Pinsky et al. 2013). Cheung et al. (2013) have developed a method for estimating the 'Mean Temperature of the Catch' (MTC) and applied it globally to reveal mid-latitude warming trends over a 36-year period. A benefit of the MTC metric is that it can be applied to systematically collected catch data. MTC is one of several climate proxies that are useful for informing coastal communities of the ocean climate challenges that threaten local food security, such as reductions in the catch potential of valuable food fish (Golden et al. 2016; Weatherdon et al. 2016).

Sample Description

To estimate changes in ocean temperature using archaeological data and the MTC metric, we first estimated proportional fish biomass from ancient Indigenous catch records. We used zooarchaeological data recovered from fine screen (3.2 and 2 mm) column samples taken from two Indigenous archaeological sites (Ts'ishaa (DfSi-16) and Huu7̲ii (DfSh-7)) on southwestern Vancouver Island, British Columbia, Canada (Figure 2). Both archaeological sites are located on small islands (<2 km^2) and have contemporaneous occupation histories spanning the past 5,000 years (McMillan and St. Claire 2005; McMillan and St. Claire 2012). Enduring human use and occupation of these two village sites is evident in extensive shell-bearing cultural sediments (i.e., shell midden) that can be broadly separated into mid-Holocene (5,000-3,000 yr BP) and late-Holocene (1,800-250 yr BP) components (Figure 3).

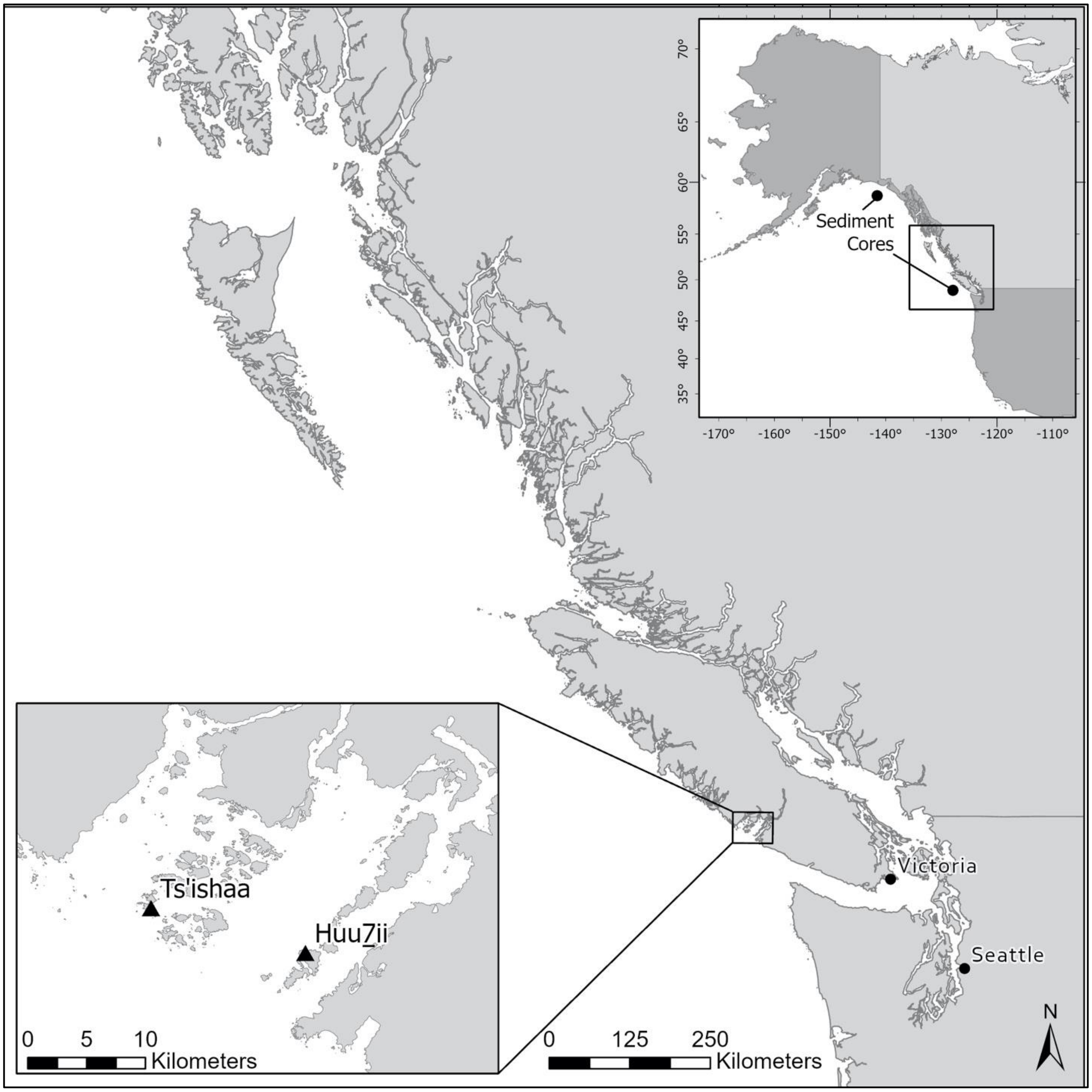

Figure 2 Faunal remains were collected from two settlement sites in Barkley Sound, on western Vancouver Island, British Columbia, Canada. Ts'ishaa is situated in Tseshaht First Nation Territory, while Huu7ii is located in Huu-ay-aht First Nation Territory. Upper right Inset map shows general locations of sediment cores from Praetorius et al. (2015). Map: Robert Gustas.

Morphological identifications of recovered skeletal elements were conducted to the most specific taxonomic classification possible, using a comparative collection at the University of Victoria, Victoria, BC, Canada (McKechnie 2005b; McKechnie 2012). The University of Victoria Zooarchaeology Comparative Collection holds one of the most extensive skeletal reference collections for Northwest Coast fauna in western North America and has helped inform osteological identifications since 1981 (McKenzie 2021). As not all skeletal elements are morphologically diagnostic to species, some specimens have lower taxonomic resolution and were lumped into larger taxonomic groupings (see Appendix A: Table 13). For osteologically distinct species (e.g., halibut (*Hippoglossus stenolepis*) and lingcod (*Ophiodon elongatus*)), we separated these taxa into their own individual groups rather than the larger taxonomic groupings of flatfish (Order Pleuronectiformes) and greenlings (Family Hexagrammidae).

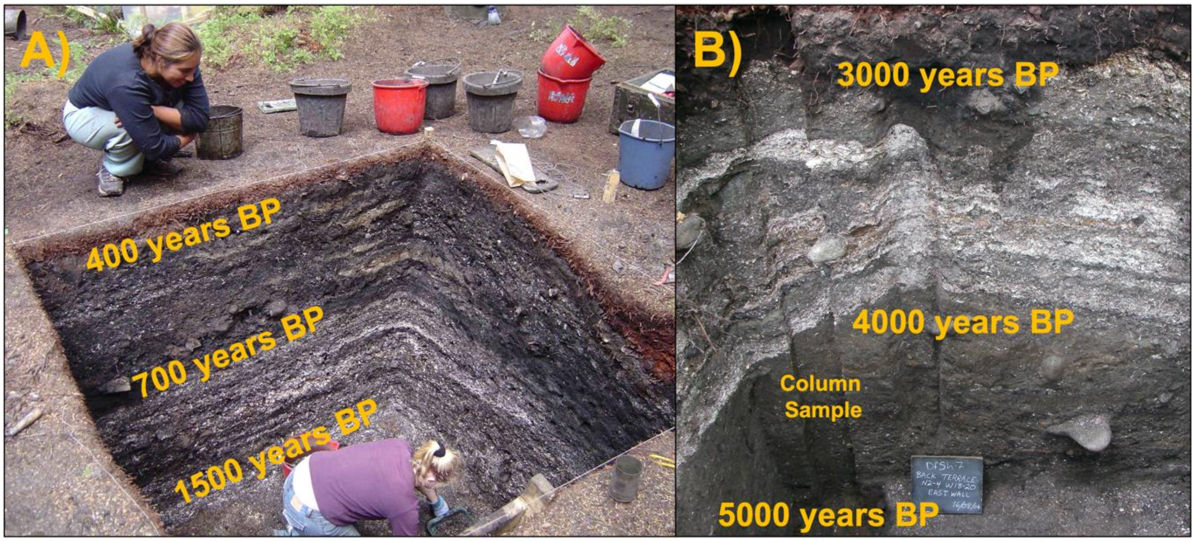

Figure 3 Excavation units from the archaeological site of Huu7ii, located in Huu-ay-aht First Nation Territory. Panel A depicts the main village component at Huu7ii, which dates between approximately 1,500-400 yr BP, while panel B depicts the back terrace component with dates spanning between 5,000-3,000 yr BP. Photos: Iain McKechnie.

Faunal specimens were identified and quantified from multiple areas of the two sites. Samples were taken from vertically spaced 5-10 cm intervals within ‘columns’ of sediment (i.e., column samples) to minimize the probability that bones from a single individual were counted twice (Figure 3). Based on the ‘Number of Individual Specimens’ (NISP), a ‘Minimum Number of Individual’ (MNI) fish for each archaeological context was then estimated from the largest number of non-repeatable elements within each column sample level. The excavated volume for each discrete column sample level represents 1.0-6.25 L of archaeological sediment and typically contains 10-200 identifiable bone specimens (see Appendix A: Table 14). Taxonomic categories with more than one species were aggregated unless there were clear size differences in the specimens (e.g., halibut vs. flatfish). Once a MNI for each column sample level was derived, we totaled minimum counts of fish according to the most specific taxonomic division possible (see Appendix A: Table 13) and calculated proportional counts for each taxonomic grouping (following McKechnie 2012). The relative proportion of MNI (% MNI) for each taxonomic grouping reflects the percentage of identified fish for each taxonomic category in the archaeological record at both Ts'ishaa and Huu7ii. For closely related species that are not morphologically distinguishable (e.g., rockfish (Family Scorpaenidae) and salmon), body size estimates were refined using existing aDNA data (Rodrigues et al. 2018) and bone measurement data for salmon vertebrae (McKechnie 2007a; McKechnie 2012) from these same sites to estimate the relative composition of species present in the archaeological assemblages (see Appendix A: Table 13).

Deriving Biomass from MNI

To derive body mass estimates for fish present in the Barkley Sound zooarchaeological record, we assembled species and genera-specific length and weight data from multiple sources to estimate body mass. We compiled regionally specific fisheries independent data, fisheries dependent data, and where available, archaeological data to best approximate the size structure of fish targeted by Indigenous fishers. For archaeological specimens, we calculated harvested body mass using regression formulae based on skeletal measurements from contemporary specimens of known length and weight (e.g., McKechnie 2007a; Nims and Butler 2019; Orchard 2003; Salmen-Hartley 2018; Sanchez 2020). In the absence of archaeological data, we preferentially used contemporary regionally specific fisheries independent scientific survey data

(Anderson et al. 2019), dockside (recreational) survey data from Barkley Sound (DFO 2001), size and weight data for comparative specimens in the University of Victoria's Zooarchaeology Comparative Collection (McKenzie 2021), and finally, more general estimates from archaeological and scientific literature (e.g., NPAFC 2021). For each species, we compiled multiple length and weight estimates and preferentially selected sources using the ranking described above (see Appendix A: Table 15).

We then calculated the median body mass (kg) for each taxonomic category by weighting each species contribution based upon the relative proportion of MNI observations (% MNI) for each species present in the archaeological record. For greater detail on the process used to calculate weighted body mass estimates, see Table 1. In addition to using the median body mass for each taxonomic group, we report the 25th and 75th quartiles to enable uncertainty estimates for biomass.

Table 1 Barkley Sound sculpin example detailing the process used in this study to derive weighted body mass estimates and weighted temperature preferences for each taxonomic category of fish. In this example, faunal remains of sculpins (recovered from both Ts'ishaa and Huu7ii) have been identified to the lowest taxonomic level possible. The 'Minimum Number of Individuals' (MNI) indicate three distinct species (Buffalo Sculpin (*Enophrys bison*), Cabezon (*Scorpaenichthys marmoratus*), Red Irish Lord (*Hemilepidotus hemilepidotus*)), one genus level designation (Irish Lord spp.), and one broader family level designation (Sculpin spp.). When MNI is summed for all levels, the taxonomic category of 'Sculpin' has a total MNI count of 49 individuals. The MNI for each species, genus and family is then divided by the total MNI to derive the proportion (%). For broader level designations (e.g., Irish Lord spp. and Sculpin spp.), body mass and temperature preferences are informed by the proportion of species level MNI counts comprising each group. In this case, Irish Lord spp. is comprised entirely of Red Irish Lord, while Sculpin spp. is weighted based on the proportion of Buffalo, Cabezon, Red Irish Lord, as well as Irish Lord spp. In other words, the 10 MNI for Sculpin spp. are comprised of all lower-level identifications based upon their proportions. Once the % contribution of each species, genus and family to the taxonomic category 'Sculpin' is known, a weighted body mass and weighted temperature preference can be generated. This is done by multiplying each species' body mass and temperature preference by their proportion (%) and then summed. The product of this is then divided by the sum of proportions for each species, genus, and family level designations.

Taxon	Buffalo Sculpin	Cabezon	Irish Lord spp.	Red Irish Lord	Sculpin spp.	Sculpin
MNI	2	12	16	9	10	49
Proportion (%)	4.1	24.5	32.7	18.4	20.4	100
Temperature Preference (°C)	9.3	9.6	4.3	4.3	6.2	6.2
Median Body Mass (kg)	0.047	3.629	0.316	0.316	1.322	1.322

For larger taxonomic categories including multiple species (e.g., salmon, sculpin (Family Cottidae), etc.), we calculated body mass by weighting the individual body mass of each species by the proportion of specimens that had been identified by skeletal measurements (Cannon and Yang 2006; Cannon and Yang 2011; Huber et al. 2011; Miszaniec 2021; Moss et al. 2014; Orchard and Szpak 2011). In the case of salmon, we calculated the body mass for each species using body mass data compiled from contemporary fisheries dependent catch landings (NPAFC 2021). We then weighted each salmon species' contribution to the larger taxonomic group using skeletal measurement data of archaeological specimens (*n* = 282) based on the size distribution of salmon vertebral measurements. Finally, we multiplied the MNI by the body mass for each taxonomic category and column sample to estimate biomass (kg). These total weights were summed and divided by the total biomass for each archaeological assemblage to determine the proportion of the catch (% Biomass). Table 2 provides a step-by-step walk-through of a hypothetical archaeological assemblage for calculating % Biomass from MNI data.

Table 2 Generating % Biomass from a hypothetical archaeological assemblage. In this example, the 'Minimum Number of Individuals' (MNI) for five taxonomic categories of fish are used to derive % Biomass estimates. Using the weighted body mass (kg) for each group of fish, body mass is multiplied by MNI to generate Biomass (kg) estimates. Biomass is then summed across all taxonomic categories to derive the Sum of Biomass. Biomass for each group of fish is then divided by the Sum of Biomass to calculate each taxonomic categories' Proportion of the Catch (% Biomass).

Taxonomic Category	Anchovy	Halibut	Herring	Perch	Rockfish	Sum of Biomass (kg)	Sum of the Proportion of the Catch (%)
MNI	15	1	30	10	8		
Body Mass (kg)	0.021	7.567	0.112	0.478	0.556		
Biomass (kg)	0.315	7.567	3.36	4.78	4.448	20.47	
% Biomass	1.5	37.0	16.4	23.4	21.7		100

Calculating ancient MTC (aMTC)

The median temperature preference for each species present in the Barkley Sound zooarchaeological record was obtained from www.fishbase.org (Froese and Pauly 2021). We then calculated a weighted median temperature preference for each taxonomic category based on the proportion of species present in the region's zooarchaeological record (% MNI). The median temperature preference for each taxonomic group was then used to calculate ancient MTC (aMTC) for each archaeological assemblage.

Following Cheung et al. (2013), aMTC was calculated using the equation provided below:

$$aMTC_{tp} = \frac{\Sigma_i^n T_i C_{i,tp}}{\Sigma_i^n C_{i,tp}}$$

Here $C_{i,tp}$ is the catch of taxonomic category i in a specific archaeological assemblage for a temporal period tp, T_i is the median temperature preference of taxonomic category i and *n* is the total number of taxonomic categories. In other words, aMTC is computed by multiplying the median temperature preference for each taxonomic category by the proportion of the catch (% Biomass). We then summed these results and multiplied the product by the total count of groups for each archaeological site and temporal period. These results were then divided by the sum of the proportion of the catch (i.e., 100%) multiplied by the number of groups for each assemblage and temporal period to derive aMTC estimates.

Calculating Modern MTC

To compare aMTC to a modern fishery dataset, we similarly examined catch records from the systematic fisheries independent Groundfish Synoptic Bottom Trawl Surveys, conducted biannually between 2004-2018 by Fisheries and Oceans Canada off western Vancouver Island (Anderson et al. 2019). We summed the total catch landings (kg) over this 14-year period for each species and then summed the total biomass for this temporal period. Following this, we divided each species' biomass by the total biomass to calculate the proportion of the catch (% Biomass). These results were then multiplied by the median temperature preference for each species representing more than 1% of the catch (n = 40 species). We then summed the product of the median temperature preferences multiplied by the proportion of the catch. Next, these results were multiplied by the total number of species (n = 40). Finally, to derive modern MTC, we divided the product of the sum multiplied by the total number of species by the sum of the proportion of the catch multiplied by the number of species.

Chronology and Radiocarbon Dating

The two mid-to-late Holocene archaeological assemblages used in this study were dated by 50 radiocarbon samples from stratigraphically associated terrestrial charcoal (see Appendix A: Table 14). The two broad age-ranges were further separated by geomorphological context, including mid-Holocene deposits on elevated terraces away from the modern shoreline and lower elevation deposits adjacent to contemporary shorelines. These site formation patterns are consistent with relative sea level histories for the region (Friele and Hutchinson 1993). Calibrated radiocarbon dates for the late-Holocene fish assemblages at Ts'ishaa and Huu7ii date to 1,800-250 yr BP and 1,500-400 yr BP, respectively. The mid-Holocene assemblages for both sites date between approximately 5,000-3,000 calibrated yr BP using the Intcal20 curve (see Appendix A: Table 14).

2.4 Results

MNI Estimates

Throughout both temporal periods, the greatest number of individual specimens (NISP) recovered from Ts'ishaa and Huu7ii are forage fish (e.g., Pacific herring and northern anchovy (*Engraulis mordax*)). When NISP were converted to MNI estimates (% MNI), forage fish were still the most numerous fish represented at both sites (Figure 4). However, when contrasting NISP and MNI we found that MNI estimates tended to elevate the importance of salmon. Due to the distinctive genus-specific texture of fragmentary salmon vertebrae which are easier to confidently identify, the frequent presence of small salmon vertebrae fragments may contribute to their overrepresentation in MNI counts. In the context of calculating MNI from small volume fine screened column samples, the presence of individual bone fragments from salmon has a stronger influence on MNI counts than more numerically abundant but smaller taxa (e.g., forage fish). This is because forage fish have smaller skeletal elements which are more challenging to confidently identify than salmon bones when fragmented.

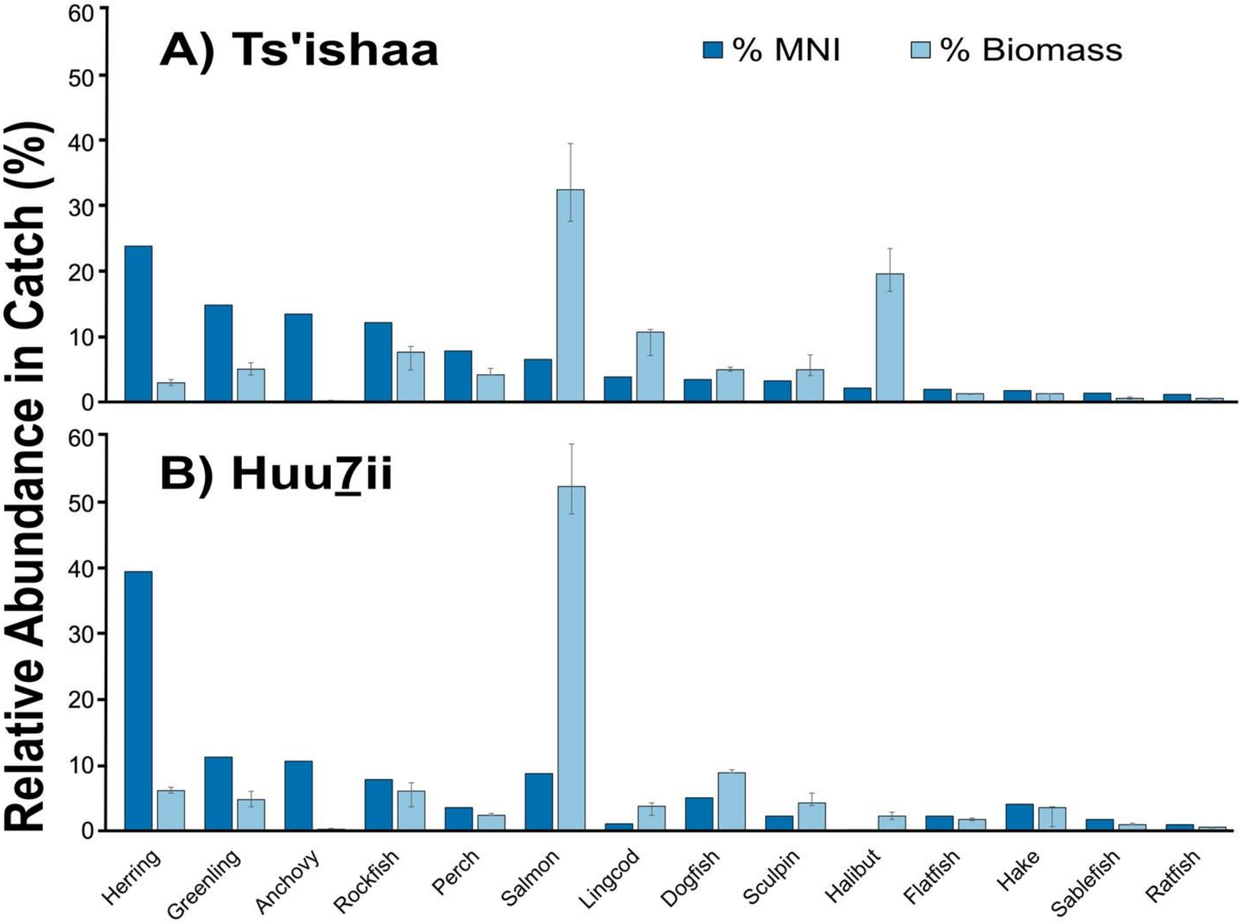

Figure 4 Taxonomic composition of the fish landed at two archaeological sites in British Columbia, Canada, over the past five millennia. Columns depict the relative proportion of the 'Minimum Number of Individuals' (% MNI) recovered from excavations and the relative proportion of biomass (% Biomass) estimated from median body mass values for each taxonomic group (Table 3). Error bars represent % Biomass using the 25th and 75th quartiles for body mass estimates.

Biomass Estimates

When MNI is subsequently converted to proportional biomass (% Biomass), salmon are estimated to contribute the single greatest fraction to fish biomass (i.e., total weight of fish caught) at both Ts'ishaa and Huu7ii (Figure 4). At Ts'ishaa, halibut ranked second after salmon, followed by lingcod, rockfish, and greenling. In contrast, proportional biomass at Huu7ii indicates that dogfish (*Squalus suckleyi*) ranked second, followed by herring, rockfish, and greenling. These trends reveal differences in the composition of fish catches across sites despite being in relative proximity (<15 km). In contrast to MNI, biomass estimates document a substantial reduction in the rank order of forage fish and a dramatic increase in salmon, halibut, and other large-bodied fishes, as would be expected when bone counts are converted to numbers of fish and then biomass.

Temporal trends show modest differences in the rank order of fish in the mid and late-Holocene components at both archaeological sites (Table 3), indicating the persistence of Indigenous fisheries and fish populations over broad time scales. Throughout the mid-Holocene, halibut represented the largest proportion of the catch (28%) at Ts'ishaa followed by salmon, lingcod, greenling, and rockfish. This differs from the late-Holocene assemblage at Ts'ishaa, where salmon (35%) dominated, followed by halibut, lingcod, rockfish, and sculpin. Meanwhile, the mid-Holocene period at Huu7̲ii indicates a strong role of salmon (53%) followed by herring, dogfish, greenling, and rockfish. The late-Holocene period continues to show salmon as the highest proportion of the catch by weight (53%), followed by dogfish, rockfish, sculpin, and hake (*Merluccius productus*).

Table 3 Comparison of the relative proportion of the ‘Minimum Number of Individuals’ (% MNI) and the relative proportion of the catch (% Biomass) for each archaeological site and temporal period under consideration. % Biomass is calculated using the median body mass estimate multiplied by MNI counts for each taxonomic grouping.

	Ts’ishaa % MNI		**Ts’ishaa % Biomass**		**Huu7ii % MNI**		**Huu7ii % Biomass**	
Approx. Age (cal yr BP)	5,000 - 3,000	1,800 - 250	5,000 - 3,000	1,800 - 250	5,000 - 3,000	1,500 - 400	5,000 - 3,000	1,500 - 400
Anchovy	7	16	<1	<1	7	13	<1	<1
Dogfish	3	4	4	6	3	6	9	9
Flatfish	2	2	1	2	<1	3	<1	2
Greenling	24	13	8	4	11	12	7	4
Hake	<1	3	<1	2	<1	6	<1	5
Halibut	4	2	28	17	<1	<1	3	2
Herring	27	23	3	3	62	28	15	4
Lingcod	5	4	13	10	<1	2	1	5
Perch	10	7	5	4	5	3	5	2
Ratfish	1	1	<1	1	1	1	1	1
Rockfish	11	13	7	8	4	10	5	7
Sablefish	1	2	<1	1	<1	3	<1	1
Salmon	6	7	28	35	6	10	53	53
Sculpin	<1	4	<1	7	1	3	2	5

MTC Calculations

Comparisons of the aMTC from both temporal components at Ts’ishaa and Huu7ii indicate cooler fish catches during the mid-Holocene (5.24°C and 5.73°C, respectively) followed by warmer temperatures during the late-Holocene occupation period (5.64°C and 5.9°C, respectively) (Figure 5). At Ts’ishaa, the range for aMTC using the median body mass estimate during the mid-Holocene is 5.22°C to 5.3°C, while the range is 5.26°C to 6.01°C for the late-Holocene component. Meanwhile, the range at Huu7ii during the mid-Holocene is 5.52°C to 6.06°C, while the range is 5.46°C to 6.15°C for the late-Holocene occupation period.

When aMTC is calculated using the 25th and 75th empirical quartiles for body mass estimates, the data reveal similar increases in the temperature of fish catches. For instance, the mid-Holocene assemblage at Ts’ishaa using the 25th quartile body mass estimate is 5.3°C (range of 5.28°C to 5.34°C) and when using the 75th quartile body mass estimate aMTC is 5.15°C (range of 5.12℃ to 5.22℃). At the same time, aMTC for Huu7ii using the 25th quartile is 5.7℃ (range of 5.5℃ to 6.02℃) and for the 75th quartile aMTC is 5.79℃ (range of 5.55℃ to 6.17℃). During the late-Holocene occupation period at Ts'ishaa, aMTC is 5.61℃ (range of 5.22℃ to 5.96℃) using the 25th quartile body mass estimate and 5.59℃ (range of 5.19℃ to 6.02℃) using the 75th quartile. At Huu7ii, the late-Holocene aMTC estimate using the 25th quartile is 5.68℃ (range of 5.34℃ to 5.87℃) and when using the 75th quartile, aMTC is 5.97℃ (range of 5.52℃ to 6.2℃). These increases in temperature are supported by geochemical data from marine sediment cores taken along the continental shelf in both BC and in the Gulf of Alaska (Figure 5; Praetorius et al. 2015). When aMTC is calculated for each respective archaeological site (i.e., representing five millennia of fishing effort), aMTC at Ts'ishaa using the median body mass estimate is 5.54℃ (5.53℃ and 5.47℃ for the 25th and 75th quartiles, respectively) while it is 5.86℃ (5.68℃ and 5.93℃ for the 25th and 75th quartiles, respectively) at Huu7ii. Most strikingly, all aMTC estimates are lower than the modern MTC calculated from the western Vancouver Island bottom trawl surveys (6.2℃).

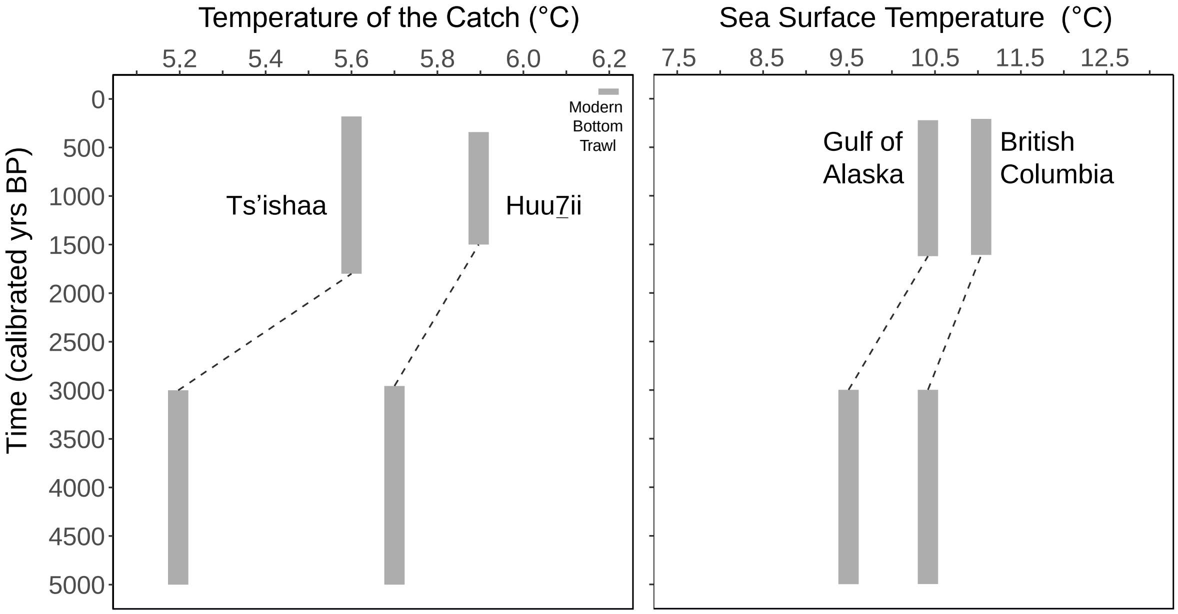

Figure 5 Estimates of ancient 'Mean Temperature of the Catch' (aMTC) presented in this study, and Sea Surface Temperature (SST) estimated from palaeoecological sediment cores from the study region (Praetorius et al. 2015). Temperature values for aMTC results are derived from the median temperature preference and median body mass estimate for each taxonomic group under study. Dashed lines indicate gaps in the zooarchaeological record (i.e., no data present for this temporal period).

2.5 Discussion

These estimates of millennial-scale increases in ocean temperature measured by ancient fisheries catches and supported by geochemical data from marine sediment cores represent the first application of the MTC method to preindustrial fisheries records using archaeological data. Considering that coastal archaeological sites with fisheries records are present across the globe, this research methodology illuminates the potential for detecting shifts in fisheries from myriad locations and timescales. This method involves several assumptions and sources of uncertainty suitable for future refinement.

We acknowledge multiple sources of uncertainty in developing the aMTC index from zooarchaeological bone count data (Figure 6). Many recognize that ancient fishing practices may not be fully represented in the archaeological record. For instance, cultural factors can have a large influence on what gets preserved in an archaeological deposit, including transport, processing techniques for consumption, storage, trade (e.g., Monks 2003), as well as spiritual considerations (e.g., Gunther 1926). In addition, biogeochemical taphonomic processes shape the formation of archaeological deposits including burial conditions, and differential preservation and fragmentation (Gifford-Gonzalez 2018). Furthermore, archaeological recovery methods such as column sampling using fine mesh sizes dramatically increases the number of elements recovered and despite smaller examined volumes, reveals equivalent measures of species richness with greater accuracy of taxonomic proportionality (McKechnie 2005a).

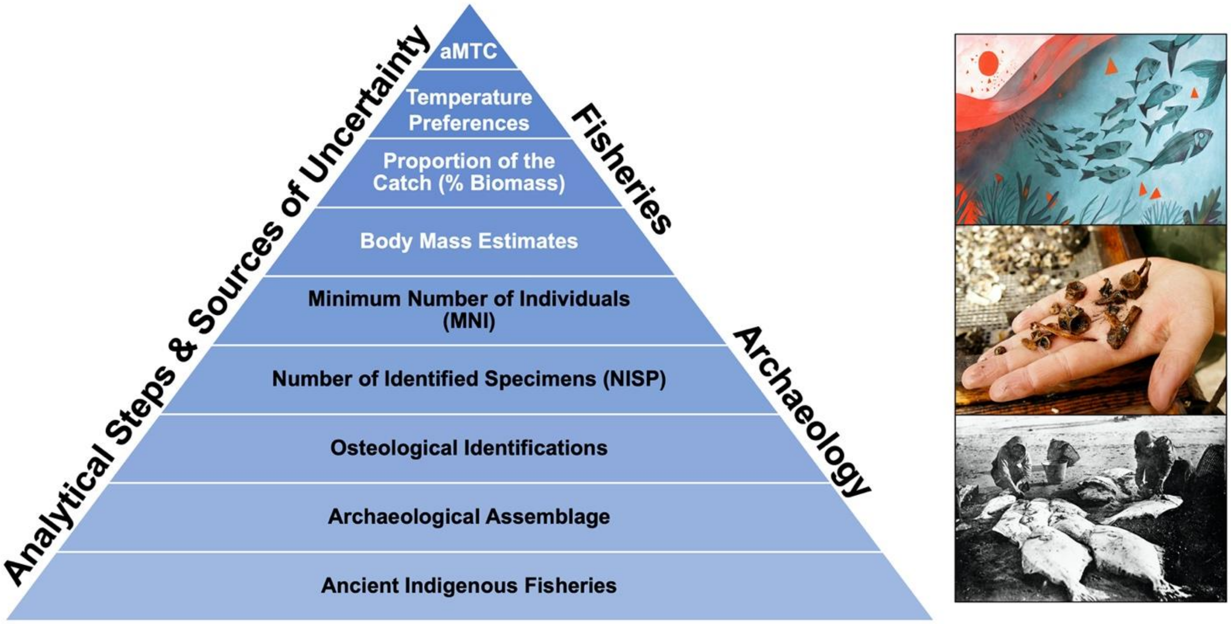

Figure 6 Analytical steps taken to generate aMTC estimates from zooarchaeological fish remains, representing five millennia of human fishing activity in the study area. Each analytical step is associated with its own uncertainty and assumptions. Sources of uncertainty include (from bottom to top of pyramid): (1) ancient Indigenous fisheries are inherently selective records (i.e., fisheries dependent data) that do not provide a complete estimate of marine community structure; (2) archaeological assemblages may not be representative of ancient Indigenous fisheries, due to taphonomic and cultural factors as well as recovery methods (e.g., screen size, sampling effort, fragmentation, etc.); (3) limitations around osteological identifications, which are influenced by the skeletal morphology of different taxa (e.g., robustness of certain skeletal elements, differences in the number of elements between taxa, identifiability of elements, etc.), the skill of each analyst conducting identifications, and the size of the comparative collection; (4) how the 'Number of Individual Specimens' (NISP) is generated from zooarchaeological analyses, which is largely determined by the identifiable portions of skeletal elements; (5) how the 'Minimum Number of Individuals' (MNI) is derived from NISP (i.e., the number of individuals based upon non-repeatable elements) and the effect that study design can have on shaping how different stratigraphic layers are considered distinct from one another; (6) uncertainty around the body mass of ancient Indigenous fish catches and how this effects relative biomass (% Biomass) calculations; (7) the challenge of using temperature preferences of modern fish to approximate the temperature preferences of ancient fish, as evolutionary and/or geographic shifts may have occurred over long time spans; and finally, (8) uncertainty around using aMTC as a temperature proxy of ancient fish catches. Photo credits (top to bottom): Luisa Rivera/Yale E360, Dylan Hillis, unknown (Washington State Archives 1890-1910: AR-07809001-ph003398).

Another concern is the accuracy and specificity of osteological identifications and the representativeness of comparative collections. In many cases, a substantial percentage of fragmentary bone specimens cannot be identified. These limitations mean that the representativeness of zooarchaeological data as a record of ancient fish landings is incomplete. As is well recognized in archaeology, MNI is fundamentally derived from bone specimen counts and can be calculated across sites levels which affects how many organisms in an archaeological context are counted (e.g., how different layers are distinct from one another). Another challenge of using zooarchaeological data to generate aMTC relates to the applicability of body mass estimates as the size, length, and body mass of fish can differ between ancient and modern fisheries data (Braje et al. 2017; McKechnie 2007a). Thus, drawing upon contemporary data to estimate ancient fish populations has limitations. Finally, median temperature preferences are based on a relationship between environmental conditions and contemporary species occurrence that may not directly reflect physiological temperature preferences, evolutionary shifts in fish physiology and temperature association given large scale ecosystem shifts in the past.

To address these limitations, we focused our analysis on two archaeological sites close to each other and with similar occupational histories, analytical methods, and rigorous sampling and quantification techniques. We then compiled an array of body mass estimates and where possible, used fisheries independent data or body mass estimates derived from archaeological assemblages using regressions or body size comparisons.

A substantive consideration relates to the accuracy of MTC as a temperature proxy, as well as the temporal resolution of archaeological data that spans millennial time scales. Such detrended estimates undoubtedly incorporate a range of climatic states that homogenize climatic variability. However, such time-averaged data also reduces potential confounding effects of fishing effort, seasonality in site use, fishing technology, and variability in climate. As the data reported on here reflect Indigenous communities living on small islands and consuming fish on a regular basis, changes in the mode of fishing over time may be independent of changing ocean temperature. To better account for the uncertainty and error in our aMTC estimates, uncertainty could be propagated throughout our calculations with hierarchical Bayesian methods whereby specified prior distributions could be associated with each estimated parameter and its associated uncertainty. Furthermore, Monte Carlo simulation methods (Yanai et al. 2010) could be used to better characterize the variability associated with MNI counts, as well as body mass and temperature preferences, as it would consider the distribution of data rather than a single summary value. Such an approach to estimating the uncertainty and error associated with aMTC estimates would strengthen the Palaeothermometer method, as it would allow for the deployment of various statistical tests.

Over the past five millennia, the composition of the catch and aMTC estimates reflect modest differences between the two villages of Ts’ishaa and Huu7ii. The difference in aMTC between sites is consistent across the two contemporaneous occupation periods, which is indicative of climatic shifts operating at a regional scale throughout the Holocene (Figure 5). The modest differences in the composition of the catch (% Biomass) between sites is intriguing, as both sites are close to one other (<15 km), as well as being situated on small islands (<2 km^2). We interpret the difference in aMTC to reflect both the local bathymetry and habitat characteristics in proximity to each village, as well as social and cultural histories associated with these politically separate communities. The two villages are associated with different contemporary First Nations and their respective territories (Tseshaht and Huu-ay-aht), which are culturally associated with territorial access to different salmon rivers, spawning grounds, rocky reef habitats, as well as delineated offshore fishing banks (McMillan and St. Claire 2005; McMillan and St. Claire 2012). The comparatively warmer aMTC values for Huu7ii may reflect the use of protected nearshore waters with a greater abundance of salmon than at the more exposed site of Ts’ishaa, which has significantly more halibut.

It is important to recognize that the inhabitants of these communities would have targeted specific species of fish at varying depths in the water column. Therefore, depending on the depths local fishers were accessing in the past, aMTC would reflect a homogenization of fishing effort based on the temperature preferences associated with different species of fish and their location within the water column. This is an important consideration, as the fisheries independent bottom trawl survey data (i.e., Anderson et al. 2019) used for the modern baseline relies upon catch data from deeper depths than traditional fishing methods would have allowed. Thus, modern fisheries independent survey data may miss important components of a cultural fishery (i.e., salmon).

As is demonstrated in our results despite the complexities listed above, the two site assemblages of Ts’ishaa and Huu7ii reveal coherent and similar trends of increasing ocean temperature over the past 5,000 years. Furthermore, our data indicate MTC is higher in the historic era, which corroborates reported increases in MTC over the past 36 years (Cheung et al. 2013; Ng and Cheung 2022). Collectively, these results indicate that preindustrial fisheries in the northeast Pacific had cooler temperatures than at present times. These findings are supported by detrended data from marine sediment cores which shows similar increases in two different regions of the northeast Pacific (Praetorius et al. 2015). Additionally, geochemical analysis of sediment cores from southwestern Yukon (Anderson et al. 2007), faunal records preserved in marine sediments in Barkley Sound (Wright et al. 2005), and geochemical analysis of archaeologically recovered fish bones from Barkley Sound (Monks 2017) reflect a similar shift in climate throughout the mid and late-Holocene. By integrating zooarchaeological and geochemical data, we provide multiple lines of evidence that document broad ocean warming in the northeast Pacific over the past five millennia. While marine sediment core records offer a regional-scale perspective of oceanographic variability, the value of our aMTC results are in their ability to show how local community fisheries responded to variability in the distribution and abundance of fish populations over time.

2.6 Conclusion

Estimating long-term climatic baselines is an essential step for understanding the magnitude of change in fisheries activities, particularly if used to better inform recovery targets that foster social and ecological well-being. This study contributes to broadening the relevance of zooarchaeological bone count data and biomass estimates in relation to research into global environmental change. The aMTC method can be further refined by quantifying uncertainty and expanded to include other archaeological datasets from different latitudes and cultural settings. Future efforts should include refinement of size estimates for zooarchaeological fish remains, species identifications, as well as quantifying variation and uncertainty at every step. While the method described here has the potential to inform preindustrial fisheries baselines globally, we acknowledge that the successful application of this approach requires detailed site-specific zooarchaeological data to inform biomass estimates. For greater consistency in the application of this method, coastal archaeologists are encouraged to develop region-specific body mass estimates for fish taxa informed by archaeological size reconstructions. In this way, the Palaeothermometer approach can be expanded to other geographic regions and temporal periods to inform preindustrial fisheries baselines.

Chapter 3: Estimating Ancient Clam Harvests from Archaeological Shell Fragments on the Northwest Coast of North America

3.1 Abstract

It is well recognized that humans have had a significant role in transforming terrestrial landscapes, yet comparatively little research has examined the long-term interactions between humans and marine ecosystems. As an applied field of research, marine historical ecology draws on archaeological, ecological, and other archival information to reveal the dynamics of marine social-ecological systems. On the Northwest Coast of North America, shellfish have long been recognized as a vital component of Indigenous economies and lifeways. However, researchers are only beginning to understand the ecological dimensions of ancient community shellfisheries, as well as predator management practices. Informed by ecological sampling and research relating to the reintroduction of sea otters (*Enhydra lutris*) in coastal British Columbia (BC), this study presents a regression-based method for determining shell length (mm) from hinge and umbo fragments of archaeologically recovered littleneck (*Protothaca staminea*), butter (*Saxidomus gigantea*) and horse (*Tresus* spp.) clams. By applying these linear regression models to an archaeological clam shell assemblage recovered from the Tseshaht First Nation village site of K̲ak̲mak̲imilh (Keith Island), Broken Group Islands, BC, we document increases in shell length and individual clam biomass over three millennia. Furthermore, size frequency distribution profiles suggest an absence of sea otter predation from ca. 1,500 yr BP to present. This methodology has broad applicability to coastal archaeological assemblages, as it allows for the reconstruction of ancient shellfish harvests and refined estimates of clam biomass. Future application of these regression-based estimates will improve knowledge of ancient shellfish harvests and how Indigenous peoples managed their shellfisheries in the deep past.

3.2 Introduction

Throughout the Northwest Coast of North America, Indigenous peoples have had an active role in managing terrestrial and aquatic ecosystems for millennia (Deur and Turner 2005; Mathews and Turner 2017; Moss 2011). By employing a diverse set of management practices, Indigenous peoples have been able to enhance the productivity and proximity of numerous natural resources (Caldwell et al. 2012; Deur et al. 2015; Groesbeck et al. 2014; Lepofsky et al. 2015; Moss 2011). Indigenous resource management systems encompass a suite of managed habitats, which challenge preconceived notions of Indigenous peoples as ‘hunter-gatherers’ or ‘fisher-hunter-gatherers’ (Deur and Turner 2005; Moss 2011).

Today, there is growing recognition that Indigenous peoples actively managed and cultivated a wide range of local resources. On the Northwest Coast, diverse practices of plant cultivation (Boyd 1999; Carney et al. 2021;; Deur 1999; Deur 2002; Deur and Turner 2005; Deur 2000; Hoffmann et al. 2016; Lyons et al. 2021; Thornton 1999; Turner and Wilson 2008; Turner 1999; Turner 2008; Turner and Clifton 2006; Turner and Peacock 2005) and fisheries management (Butler and Campbell 2004; Haggan et al. 2006; Langdon 2006; Menzies and Butler 2007; Thornton et al. 2010) reflect the sustained and intentional activities of Indigenous peoples over millennia. In fact, the use of size selective fishing technology, rights-based harvesting restrictions, ceremonial controls, and traditional knowledge have all contributed to the resilience of coastal marine ecosystems in the region for millennia (Caldwell et al. 2012; Salomon et al. 2018).

Numerous species of clam are found throughout the Northwest Coast and have featured as a reliable and nutritious source of food for people since the earliest documented settlements in the region (Cannon et al. 2008; Moss 1993; Moss 2011). As an abundant and readily available intertidal food item, littleneck (*Protothaca staminea*), butter (*Saxidomus gigantea*) and horse (*Tresus* spp.) clams have supported Indigenous communities for millennia and represent a key source of economic and cultural significance (Deur et al. 2015; Moss 1993). As documented in ethnographic accounts and the archaeological record, clams are featured as an important source of food in local communities (Deur et al. 2015; Ellis and Swan 1981; Ellis and Wilson 1981). Throughout the region, archaeological assemblages regularly consist of huge quantities of shell that form distinct stratigraphic deposits, which includes anthropogenic shell used for landscape engineering and shorelines modifications (Grier et al. 2017; Onat 1985; Letham et al. 2020). Archaeological investigations into past shellfish management practices, coupled with traditional knowledge and ecological science, have brought increased attention to the role of local shellfisheries in providing food security for coastal communities (Groesbeck et al. 2014; Lepofsky et al. 2015; Moss 1993).

Sea otters exist as keystone predators and can have profound effects on marine ecosystems, particularly shellfish communities (Gregr et al. 2020; Foster et al. 2021; Markel and Shurin 2015). Currently, sea otters are rapidly recolonizing coastlines throughout the Northwest Coast, which poses a serious threat to the food security of coastal Indigenous communities (Burt et al. 2020; Pinkerton et al. 2019). Research on California mussel (*Mytilus californianus*) shell has established that the presence of sea otters can shape the size distribution profile of mussel harvests (Singh et al. 2013). Recent research has explored the former prevalence of sea otters by examining ancient Indigenous mussel harvests using linear regression models (Slade et al. 2022). As clams are also a valued prey item for sea otters, similar analyses on clams are applicable to evaluating the presence or absence of sea otters, and by extension, the degree to which people managed otter populations in the past.

Throughout the Northwest Coast, clam are ubiquitous in archaeological assemblages, reflecting their sustained use by coastal Indigenous peoples. However, archaeologically recovered shellfish remains are often fragmentary, which limit our understanding of the size profile of ancient shellfish harvests. Previous studies have developed size-based estimation methods to determine the average body mass of clams harvested in the past (Croes 1992; Moss 1993). While such methods fail to account for the presence of shell fragments within shellfish assemblages, they also ignore variability within size estimates. More recent research relying upon ecological and archaeological surveys have developed size frequency distribution profiles using linear regression models (e.g., Daniels 2014; Grone 2020), although these tend to be limited to a specific species or study area. Therefore, refined methods are required for evaluating the scale of ancient shellfisheries and the effect humans had on marine systems in the deep past.

This study presents a regression-based method for determining shell length (mm) from the often-fragmentary remains of littleneck, butter, and horse clams. These linear regressions are then applied to an archaeological clam shell assemblage to estimate the size profile of ancient clam harvests. Finally, shell length-to-total weight and shell length-to-wet meat weight conversion factors are then used to estimate biomass distribution profiles for each species of clam. The results of our study document an increase in shell length and individual clam biomass over three millennia at the site of K̲ak̲mak̲imilh (Keith Island), Broken Group Islands, Tseshaht First Nation Territory, Barkley Sound, British Columbia (BC), Canada. Furthermore, size frequency distribution profiles suggest a possible absence of sea otter predation from ca. 1,500 yr BP to present. This methodology has broad applicability to coastal archaeological assemblages, as it allows for the reconstruction of ancient shellfish harvests and refined estimates of individual clam biomass. Future application of these regression-based estimates will improve knowledge of ancient shellfish harvests and how Indigenous peoples managed their shellfisheries in the deep past.

3.3 Materials and Methods

Sample Selection

To derive and evaluate biometric relationships for our regression models, 75 horse (*Tresus* spp.), 108 butter (*Saxidomus gigantea*) and 110 littleneck (*Protothaca staminea*) contemporary (i.e., modern) clam shells were collected from locations around Vancouver Island and the Central Coast of BC, Canada. Clams were obtained from a range of coastal embayments surrounding Quadra Island (*n* = 186), the Central Coast (*n* = 82), and western Vancouver Island (*n* = 8) (Table 4). Clam shells were collected from the mid-to-low tide on unmodified beaches and shell conditions ranged from relatively untouched to heavily worn, due to natural weathering processes.

To estimate the size profile of ancient clam harvests, we drew upon archaeologically recovered clam shells from the village site of K̲ak̲mak̲imilh (Keith Island), located in the Broken Group Islands, Tseshaht First Nation Territory, Barkley Sound, BC. Of the total 461 archaeological clam shells analyzed, 65 were horse, 245 were butter, and 151 were littleneck (Table 5). All archaeological clam shells were recovered using ‘column sampling’ methods (McKechnie 2005a), and in instances that paired valves were obtained, we preferentially measured only one valve so that the same individual was not measured twice.

Table 4 Sample locations of modern clam specimens used in this study, including the number of sampled specimens (*n*) for each location.

Sample Location	Butter (*n*)	Littleneck (*n*)	Horse (*n*)
Central Coast	15	40	27
Quadra Island	84	70	32
Barkley Sound	3	0	5
Unknown	6	0	11
Total	**108**	**110**	**75**

Table 5 Presented in this table are the number (*n*) of archaeological clam shells used to generate size estimates, which are broken down by species and the excavation unit each shell was recovered from. All archaeological clam shells were recovered from the site of K̲ak̲mak̲imilh (306T) located on Keith Island in the Broken Group Islands, Tseshaht Territory, Barkley Sound.

Unit No.	Butter (*n*)	Littleneck (*n*)	Horse (*n*)
306T-7	143	79	58
306T-8	87	55	7
306T-10	15	17	0
Total	**245**	**151**	**65**

Measurement Criteria

For each species of clam used in this study, we selected morphologically distinctive markers on the shell (e.g., the length of the hinge, the thickness of the umbo, and the dorsal length) to develop our regression formula (Figure 7). As these attributes form the most robust portion of the shell (e.g., umbo and hinge) and are often recovered in small volume archaeological samples, we focused our measurements on these distinctive markers (e.g., Singh et al. 2015). In fact, during archaeological analyses the umbo can be used to estimate the 'Minimum Number of Individuals' (MNI), as it is non-repeatable and less susceptible to fragmentation during recovery (Giovas 2009). We chose to measure either left or right vales for each sampled location to minimize the chance of repeat measurements on the same individual specimen. As modern shells were collected from unmodified beach deposits, conditions varied substantially, which broadly reflects taphonomic processes found in archaeological deposits and is thus a comparable measure of uncertainty. While there is potential for allometric variation in shell growth within the intertidal zone (Singh et al. 2015; Thakar et al. 2017), by focusing our morphometric measurements on distinctive markers we can determine dorsal shell length within a reasonable degree of accuracy.

Because shell valves recovered from archaeological assemblages are overwhelmingly fragmentary, we measured multiple morphological markers on individuals clam shells to account for different recovery conditions. While this method reveals differences in predictive strength for the various shell attributes, the value of this approach is that uncertainty can be quantified. In this way, deriving length estimates from fragmentary specimens has great potential for quantifying the size profile of past shellfish harvests and the resilience of Indigenous aquaculture practices. To build the predictive models we used a simple ordinary least squares regression formula (Table 5). This was done to determine dorsal shell length from shell fragments, specifically the umbo and hinge.

To quantify measurement uncertainty for both the modern and archaeological clam shell assemblages, we conducted repeated measures of each measurement type to assess observer and inter-observer error. For modern clam shells, inter-observer error was calculated by measuring a random subsample of 10 individual clams for each species using each measurement type by three analysists (i.e., observer 1, 2, and 3). Inter-observer error for clams recovered from archaeological deposits was calculated in the same way as modern clams. Finally, observer error for archaeological clam shell measurements is based on repeat measures taken by observer 1 at the beginning, middle, and end of analysis.

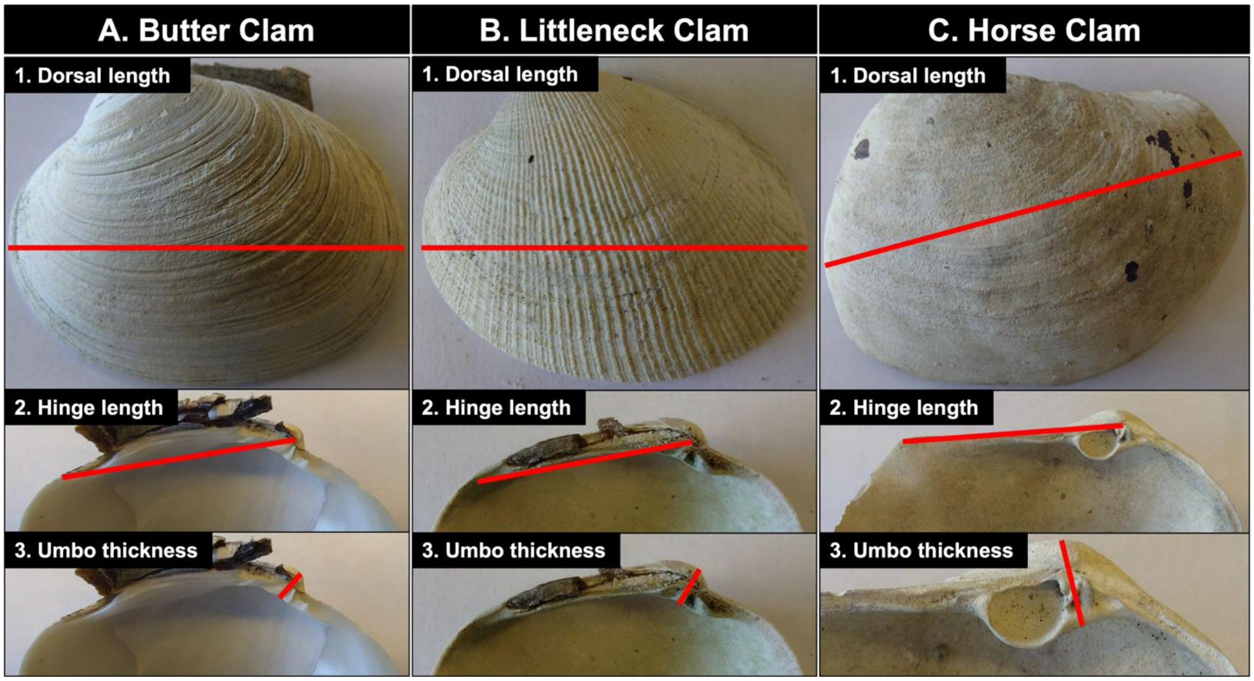

Figure 7 Measurements made on butter, littleneck, and horse clams for generating linear regression models to estimate dorsal shell length.

Table 6 Regression equations for estimating dorsal length of littleneck, butter, and horse clams from measurements of the umbo and hinge, including the R^2 values, the residual standard error (±), and sample size (*n*).

Species	Measurement Description	Regression Equation	R^2 Value	SE (±)	*n*
Protothaca staminea	Umbo	Length = 5.9771 x + 6.6276	0.92	0.56	110
Protothaca staminea	Hinge	Length = 1.7599 x + 9.4595	0.96	1.31	110
Saxidomus gigantea	Umbo	Length = 8.7938 x + 5.2336	0.91	0.69	108
Saxidomus gigantea	Hinge	Length = 1.5151 x + 15.474	0.89	4.31	108
Tresus spp.	Umbo	Length = 6.3317 x + 17.402	0.96	1.31	75
Tresus spp.	Hinge	Length = 1.7218 x + 13.573	0.95	4.24	75

Length-to-Weight Calculations

Once the archaeologically recovered clam shells were measured, we applied our regression-based formula to develop a size distribution profile of ancient shellfish harvests at Ḵaḵmaḵimilh, based on the estimated dorsal length for each individual clam. Following this, we applied length-to-weight conversion factors for all species to estimate the total weight (g) and wet meat weight (g) of each individual clam. Total clam weight (g) was calculated using the formula presented below (following Bradbury et al. 2005):

$$Weight = aL^b$$

Where a is the parameter estimate for a specific species of clam, L is the predicted dorsal length for each individual clam, and b is the parameter estimate for a specific species of clam. For both littleneck and butter clams, a and b were derived from Bradbury et al. (2005) using length-weight models for clams sampled from “Bivalve Region 1: Juan de Fuca.” Parameter estimates (i.e., a and b) for horse clam were derived from Barber et al. (2012) using data from Puget Sound, Washington.

To calculate wet meat weight (g) from archaeological shell size estimates, we used the formula presented below (following Kvitek et al. 1992):

$$Wet\ Meat\ Weight = aL^b$$

Where a is the parameter estimate for a specific species of clam, L is the predicted dorsal length for each individual clam, and b is the parameter estimate for a specific species of clam. For each species of clam under examination, length-to-wet meat weight conversion factors were developed by Kvitek et al. (1992) using ecological data from the Kodiak Archipelago, Alaska.

3.4 Results

Linear Regressions

All linear regressions used in this study show a strong predictive relationship, which indicates a close association between dorsal length and measures of the umbo and hinge (Figure 8). For littleneck clam, the R^2 values range from 0.96 (hinge length) to 0.92 (umbo thickness), indicating that 92 to 96% of variability in littleneck length can be predicted based on umbo thickness and hinge length. The results for butter clam reveal R^2 values ranging from 0.89 (hinge length) to 0.91 (umbo thickness), which suggests a strong relationship where 89 to 91% of variability is captured. Finally, the R^2 values for horse clam is 0.97 (hinge length) and 0.96 (umbo thickness), again indicating a strong relationship between the length of the hinge and the thickness of the umbo to dorsal shell length.

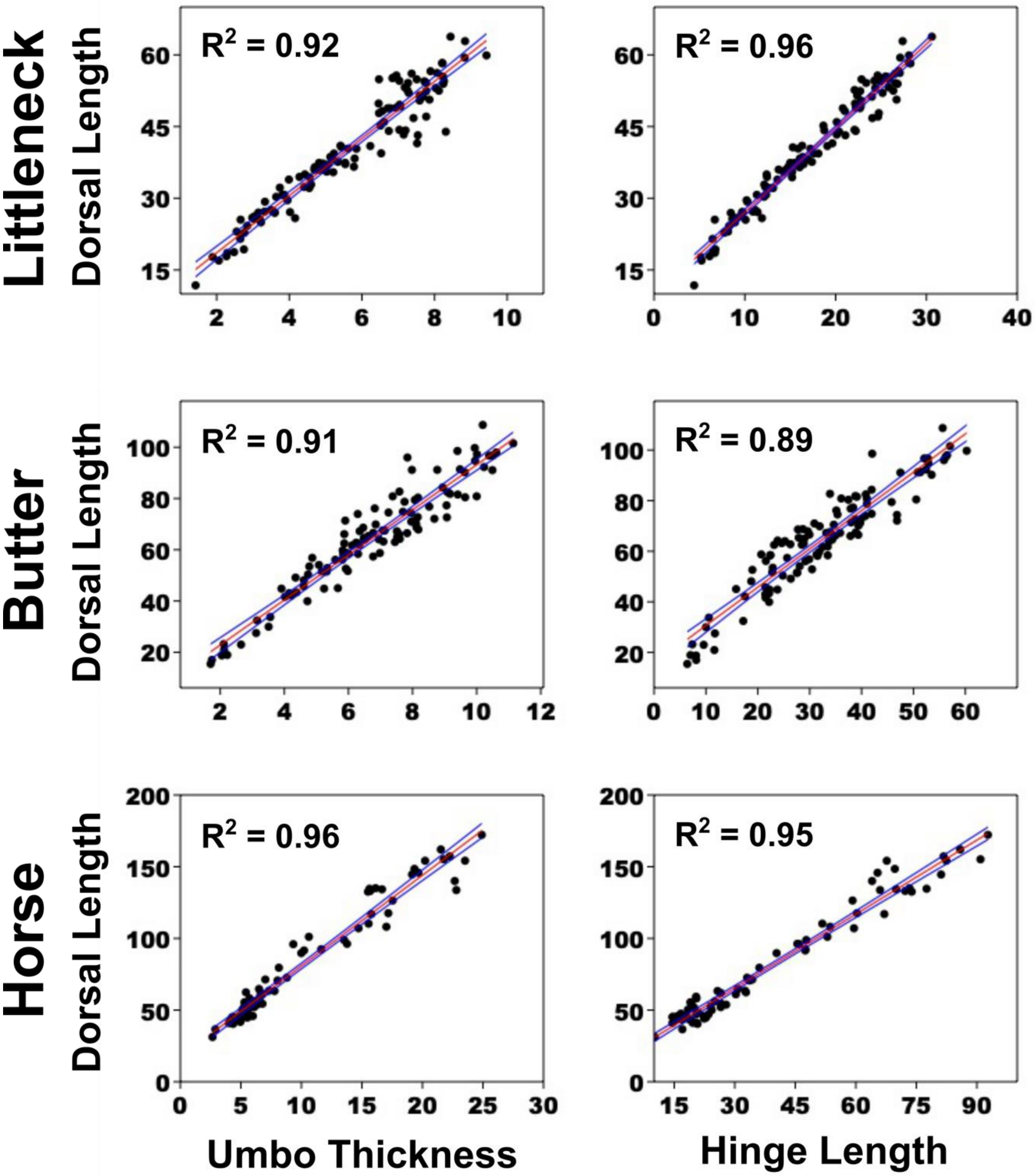

Figure 8 Linear regressions of modern littleneck (*n* = 110), butter (*n* = 108), and horse (*n* = 75) clams comparing hinge length (mm) and umbo thickness (mm) to dorsal length (mm) for beach collected specimens. Note, blue trend lines represent 95% confidence intervals.

Observer & Inter-Observer Error

Based on repeat measures of modern clam shells, inter-observer error was calculated for each measurement type (*n* = 3) and each species of clam (*n* = 3). Irrespective of which species is being examined, hinge length consistently generated the largest inter-observer error compared to other measurement types (Table 7). This is likely due to increased measurement variability associated with the hinge as opposed to the umbo or dorsal surface, due to less distinctive morphological markers on the hinge. That said, the mean of the standard deviation across 10 randomly resampled individuals for each species (i.e., total resampled = 30) is equal to or less than 1 mm for each measurement type.

For archaeologically recovered clam shells, observer error is calculated from three repeated measures of 10 control samples per species, which occurred at the beginning, middle and end of analysis. In-line with results for modern specimens, the mean of the standard deviation indicates that the hinge is the most variable measurement type across all species (Table 8). Inter-observer error of archaeological specimens suggests there is moderately greater variation across measurement types and species when multiple analysists are examining the same individual specimens. However, the mean of the standard deviation shows that inter-observer error does not exceed 1.5 mm (Table 8).

Table 7 This table presents the average of the standard deviation for each measurement type (*n* = 3) for each species under consideration (*n* = 3) using modern clam shells. The standard deviation is calculated from repeated measures of 10 random samples for each species. The standard deviation for each measurement type is then averaged across all 10 samples for each species, to produce an average of the standard deviation. Inter-observer error (mm) is calculated from repeat measures of each respective sample by observer 1, observer 2, and observer 3.

Species	Measurement Description	Avg. SD Inter-Observer Error (mm)
Protothaca staminea	Dorsal	0.21
Protothaca staminea	Umbo	0.52
Protothaca staminea	Hinge	1.0
Saxidomus gigantea	Dorsal	0.26
Saxidomus gigantea	Umbo	0.22
Saxidomus gigantea	Hinge	0.38
Tresus spp.	Dorsal	0.31
Tresus spp.	Umbo	0.52
Tresus spp.	Hinge	1.25

Table 8 This table presents the average of the standard deviation for each measurement type (*n* = 3) for each species under consideration (*n* = 3) using archaeologically recovered clam shells. The standard deviation is calculated from repeated measures of 10 control samples for each species. The standard deviation for each measurement type is then averaged across all 10 controls for each species, to produce an average of the standard deviation. Observer error (mm) is based on three repeat measures of each control sample taken at the beginning, middle, and end of analysis by observer 1. Inter-observer error (mm) is calculated from the average value for each control sample measured by observer 1 (*n* = 3) and measurements of each control sample by observer 2 and observer 3.

Species	Measurement Description	Avg. SD Observer Error (mm)	Avg. SD Inter-Observer Error (mm)
Protothaca staminea	Dorsal	0.12	0.17
Protothaca staminea	Umbo	0.16	0.22
Protothaca staminea	Hinge	0.69	1.2
Saxidomus gigantea	Dorsal	0.23	0.27
Saxidomus gigantea	Umbo	0.15	0.48
Saxidomus gigantea	Hinge	0.63	1.43
Tresus spp.	Dorsal	0.41	0.21
Tresus spp.	Umbo	0.55	0.61
Tresus spp.	Hinge	1.26	0.79

Archaeological Size Profiles

By applying the linear regression models (Table 6) to the archaeological clam shell assemblages at K̲ak̲mak̲imilh, we are able to document Indigenous harvest profiles from clam size frequency distributions over three millennia (Figure 9). Across all three excavation unit assemblages, the median estimated dorsal length for littleneck clam using the umbo regression is 37.4 mm and 49.1 mm for the hinge regression (Table 9). The median predicted dorsal length for butter clam is 52.5 mm and 68.3 mm, while the median length for horse clam is 75.3 mm and 88.0 mm using the umbo and hinge regression models, respectively. Interestingly, the predicted dorsal length using the hinge measurement produces larger length estimates than the umbo for all species (Table 9). Therefore, the umbo measurement likely produces more conservative dorsal length estimates than the hinge.

Furthermore, the estimated dorsal length for all species, measurement types, and excavation units considered in this study reveal size frequency distribution profiles that are not normally distributed (Figure 9; Figure 10; Figure 11). For instance, the violin plots presented in Figure 10 are all right skewed when dorsal length is estimated using the umbo regression model. Across all unit assemblages, the skewness value for littleneck clam using the umbo regression model is 0.68, butter is 0.68, and horse is 0.83. Meanwhile, the skewness value for littleneck clam using the hinge regression model is 0.01, butter is 0.39, and horse is -0.17. Additionally, size distributions for littleneck and butter clams recovered from excavation unit 10 are truncated (Figure 10; Figure 11).

When estimated dorsal shell length is examined for each excavation unit at K̲ak̲mak̲imilh (e.g., units 306T-7, 306T-8, and 306T-10), the data indicate modest trends in clam size distributions over time (Figure 11). Radiocarbon dating of each excavation unit at K̲ak̲mak̲imilh places unit 10 as the earliest component of the site (ca. 3,000-2,000 yr BP), while unit 8 represents the middle occupation phase (ca. 1,500-700 yr BP) and unit 7 the latest (ca. 1,000-70 yr BP) (McKechnie and St Claire n.d.). Size frequency distributions of archaeological clam shell assemblages show modest shifts in clam sizes over time (Figure 11). Using the umbo regression model, the median predicted dorsal length for littleneck clams recovered from unit 10 column samples is 32.3 mm, unit 8 is 37.1 mm and unit 7 is 38.6 mm (Table 10). The results of a Mann-Whitney Pairwise test (Table 11) indicate a statistically significant increase in littleneck size between units 10 and 8, with no significant increase between units 8 and 7. For butter clams, the median estimated dorsal length for shells recovered from unit 10 is 48.9 mm, unit 8 is 50.7 mm and unit 7 is 54.0 mm (Table 10). There is no significant increase in size between unit 10 and unit 8 butter clams, however there is a statistically significant increase between unit 8 and unit 7 (Table 11). The median predicted dorsal length of horse clams in unit 8 is 77.6 mm and 72.8 mm in unit 7 (Table 10), although this decrease in size is not statistically significant (Table 11). Overall, the data indicate an increase in littleneck and butter clam size over time, with no detectable shift for horse clams.

The value in this methodological approach is our ability to estimate clam size frequency distributions over archaeological time scales. In this way, researchers are able to examine questions relating to shifts in clam size over time. For instance, Foster (2021) explored the role sea otters and humans had on ancient Indigenous shellfisheries in coastal BC. Such an approach is applied in this study.

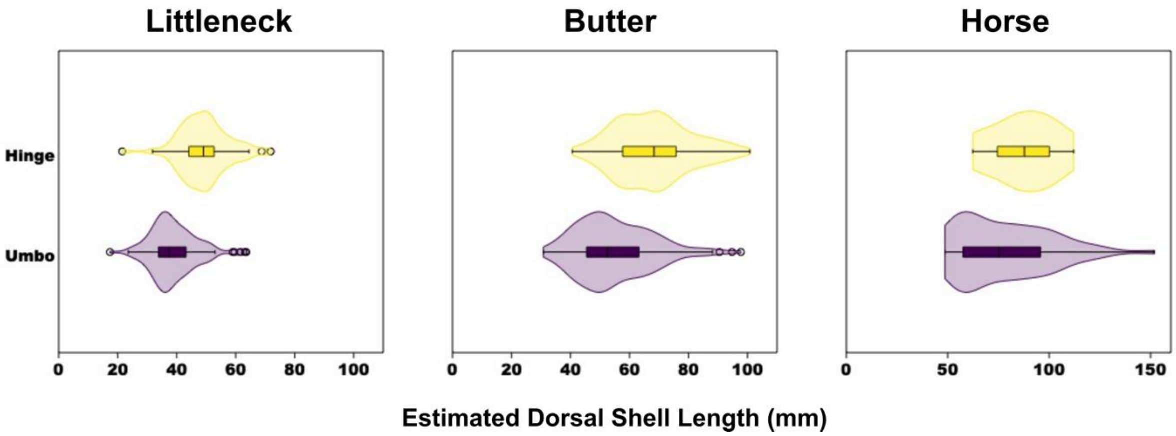

Figure 9 Estimated dorsal length (mm) size frequency distributions for all species of clam across all shellfish assemblages using the umbo and hinge regression models. These data document three millennia of clam harvesting effort at K̲ak̲mak̲imilh.

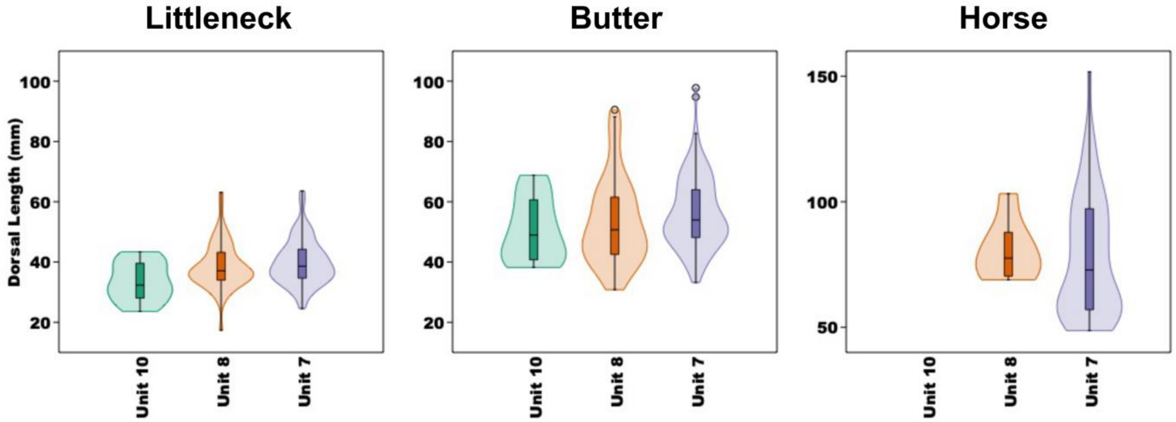

Figure 10 Estimated dorsal length (mm) size frequency distributions for each species and excavation unit at the site of K̲ak̲mak̲imilh. Unit 10 represents the earliest occupation phase (i.e., oldest), while unit 8 is intermediate and unit 7 is the latest (i.e., youngest).

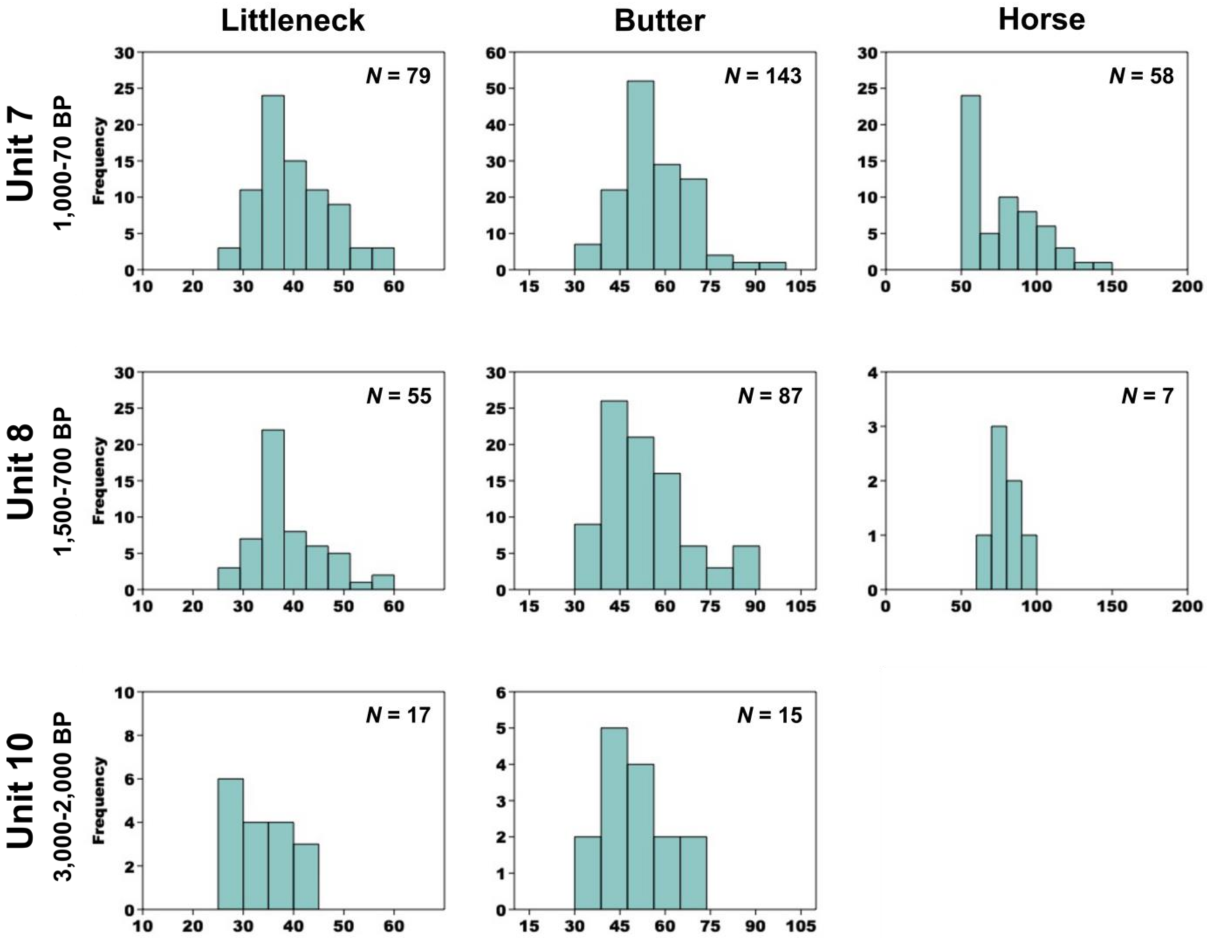

Figure 11 Archaeological size frequency distributions (i.e., predicted dorsal length (mm)) for each species of clam using the umbo regression formula developed in this study. Note, sample sizes used to predict dorsal length from umbo measurements vary considerably depending on each excavation unit, due to differential preservation of shell fragments. Each excavation unit represents a different temporal phase of occupation at K̲ak̲mak̲imilh (e.g., unit 10 is the earliest occupation phase, unit 8 is intermediate, while unit 7 is the latest). Furthermore, there were no horse clams present in unit 10 to develop size frequency distributions.

Table 9 This table presents the median, the mean, and the standard deviation (SD) of the estimated dorsal length (DL) for archaeologically recovered clam shells using regression formula presented in Table 5.

Species	Regression Type	Median DL (mm)	Mean DL (mm)	SD Dorsal Length (mm)
Protothaca staminea	Umbo	37.4	38.8	7.8
Protothaca staminea	Hinge	49.1	49.1	8.5
Saxidomus gigantea	Umbo	52.5	54.8	12.8
Saxidomus gigantea	Hinge	68.3	67.8	12.7
Tresus spp.	Umbo	75.3	78.0	22.8
Tresus spp.	Hinge	87.8	88.0	16.2

Table 10 This table presents the estimated median dorsal length (mm) and sample number (*n*) for each species of clam recovered from units 7, 8, and 10 at K̲ak̲mak̲imilh. Note, predicted dorsal length is calculated using the umbo regression developed in this study.

Species	Unit No.	Median DL (mm)	*n*
Protothaca staminea	7	38.6	79
Protothaca staminea	8	37.1	55
Protothaca staminea	10	32.3	17
Saxidomus gigantea	7	54.0	143
Saxidomus gigantea	8	50.7	87
Saxidomus gigantea	10	48.9	15
Tresus spp.	7	72.8	58
Tresus spp.	8	77.6	7
Tresus spp.	10	NA	0

Table 11 Results of the Mann-Whitney Pairwise test that examines changes in clam harvest profiles (i.e., predicted dorsal length using umbo regression) across column sample assemblages for each excavation unit at K̲ak̲mak̲imilh. *P*-values are provided for each unit and species under study, with statistically significant relationships denoted in bold. For littleneck clam, results indicate a statistically significant shift in harvest size between unit 10 and units 8 and 7. For butter clam, the only statistically significant shift detected is between units 8 and 7. Finally, there is no significant changes detected between units 8 and 7 for horse clam.

Mann-Whitney Pairwise Test			
Littleneck	Unit 10	Unit 8	Unit7
Unit 10		**0.017**	**0.003**
Unit 8	**0.017**		0.299
Unit 7	**0.003**	0.299	
Butter	Unit 10	Unit 8	Unit7
Unit 10		0.568	0.069
Unit 8	0.568		**0.024**
Unit 7	0.069	**0.024**	
Horse		Unit 8	Unit 7
Unit 8			0.415
Unit 7		0.415	

Biomass Estimates

When length-to-weight conversion factors are applied to the estimated dorsal length for each clam shell assemblage, the data show that all size distribution profiles are right skewed (Figure 12; Figure 13). Such distribution profiles are characterized by a presence of larger individuals, which suggest an absence of sea otter predation in the area. Interestingly, all distribution profiles for excavation unit 10 clams are truncated (Figure 13). These trends in unit 10 may be a product of small sample sizes, alternatively it may reflect sea otter predation as otters tend to limit the size shellfish are able to reach (Kvitek et al. 1992; Singh et al. 2013).

All median total weight (g) estimates for archaeologically recovered clam shells across all unit assemblages are presented in Table 12. Based on the estimated median total weight (g) for each species of clam, littlenecks are generally lighter than butter clams, while horse clams are the heaviest by biomass. These results are consistent with other ecological studies that compare clam biomass across species (e.g., Groesbeck et al. 2014; Kvitek et al. 1992).

Across all excavation units, the median wet meat weight (g) estimates reveal similar trends as documented in the size frequency distributions for total clam weight (Figure 12). The median wet meat weight estimate for individual littleneck clams is 5.1 g and 9.0 g using the umbo and hinge regressions, respectively (Table 12). For individual butter clams, the median wet meat weight estimate is 13.0 g and 26.9 g using the umbo and hinge regression models, respectively. Finally, the median wet meat weight estimate for individual horse clams using the umbo regression model is 53.6 g, while it is 86.1 g using the hinge regression models. Ultimately, these discrepancies in body mass and length estimates using the umbo and hinge regression models are consistent across all species and excavation units, which suggest differences in the predictive strength of each measurement type. Therefore, we recommend using the umbo model where possible, as it provides more conservative estimates than the hinge model.

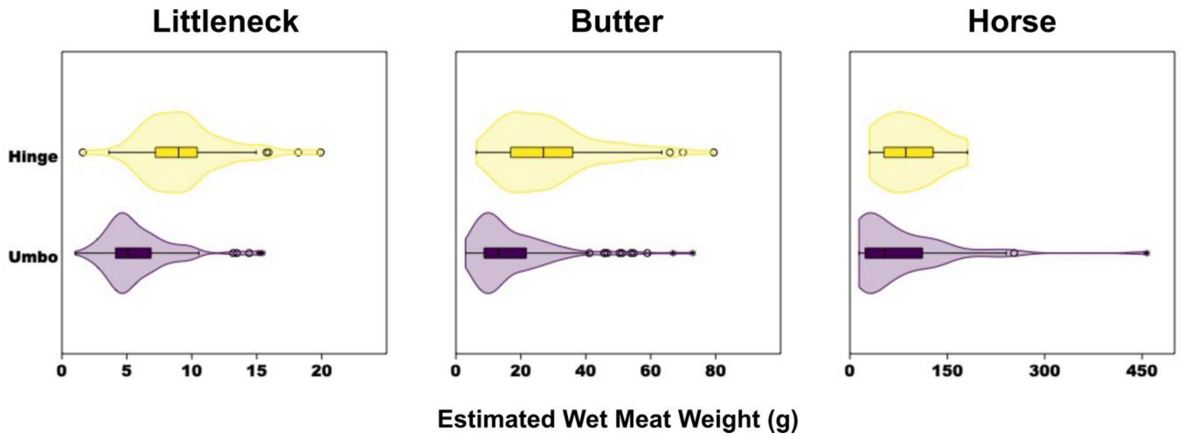

Figure 12 Estimated wet meat weight (g) size frequency distribution profiles for all species of clam across all shellfish assemblages using the umbo and hinge regression models. These data document three millennia of clam harvesting effort at K̲ak̲mak̲imilh.

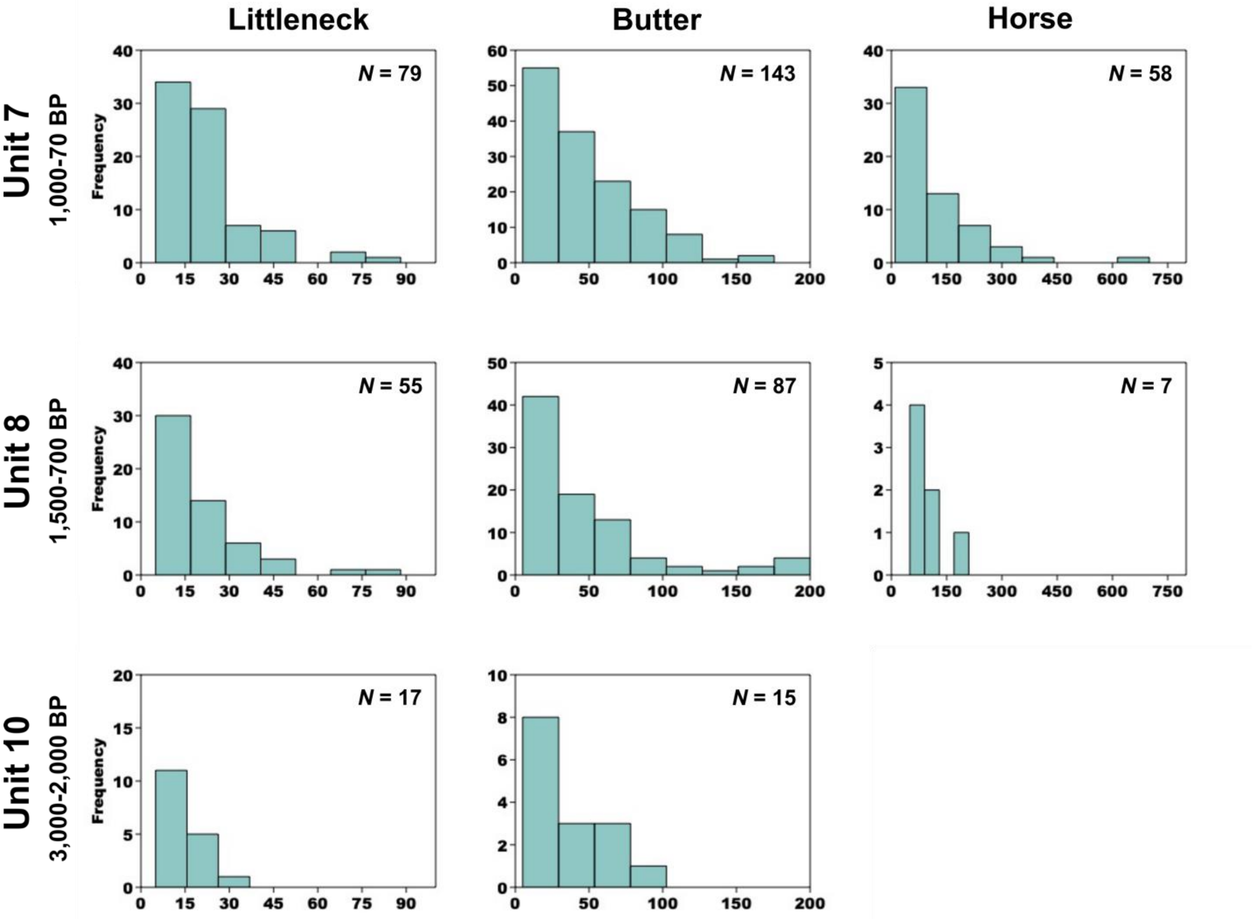

Figure 13 Archaeological size frequency distribution profiles (i.e., estimated total weight (g)) for each species and excavation unit using the umbo regression formula developed in this study. Note, sample sizes used to estimate total clam weight from dorsal length estimates vary considerably depending on each excavation unit, due to differential preservation of shell fragments. Each excavation unit represents a different temporal phase of occupation at K̲ak̲mak̲imilh (e.g., unit 10 is the earliest occupation phase, unit 8 is intermediate, while unit 7 is the latest). Note, there were no horse clams present in unit 10 to develop size frequency distributions.

Table 12 This table presents the estimated median total weight (g) and estimated median wet meat weight (g) for archaeologically recovered clam shells used in this study. Shell lengths were estimated using regression formula presented in Table 5, while length-weight conversion factors were calculated using the formula presented in Bradbury et al. (2005) and Kvitek et al. (1992). Alpha and Beta parameter estimates for littleneck and butter clams were drawn from Bradbury et al. (2005) Bivalve Region 1 (Strait of Juan de Fuca), while parameter estimates for horse clams were obtained from Barber (2012) using data collected from Puget Sound. To calculate wet meat weight, Alpha and Beta parameter estimates for littleneck, butter, and horse clams were drawn from Kvitek et al. (1992) using ecological data collected from the Kodiak Archipelago.

Species	**Regression Type**	**Total Weight (g)**	**Wet Meat Weight (g)**	***n***
Protothaca staminea	Umbo	16.8	5.1	151
Protothaca staminea	Hinge	38.3	9.0	66
Saxidomus gigantea	Umbo	34.6	13.0	245
Saxidomus gigantea	Hinge	82.7	26.9	96
Tresus spp.	Umbo	80.1	53.6	65
Tresus spp.	Hinge	127.8	86.1	8

3.5 Discussion

The results of this study suggest there is a strong linear relationship between the length of the hinge, the thickness of the umbo, and the dorsal length of littleneck, butter, and horse clams. For all species considered in this analysis, 89 to 97% of the variability in shell length is captured in these linear regression models. These findings indicate that this method is an effective technique for estimating the dorsal length of clam shells from often fragmentary remains, which are common in archaeological deposits.

A limitation in this study relates to the geographical range encompassed in the modern collected specimens, which may have variability in growth conditions represented across broad spatial and temporal scales (Singh and McKechnie 2015; Slade et al. 2022). However, these regressions aim to incorporate uncertainty across a broad spatial scale as uncertainty would have occurred over archaeological time scales. The strength of these linear regression models indicate that hinge length and umbo thickness are effective predictors of dorsal shell length, irrespective of sampling location or species. Yet, when observer and inter-observer error are considered

(Table 7; Table 8), measurements of the hinge are associated with greater variability compared to the umbo. This is likely due to less distinctive morphological markers on the hinge, which influences the accuracy of measurements. These findings support the applicability of this method to assess the size of fragmentary specimens recovered from coastal archaeological assemblages.

The data presented in this study suggests a preference for medium size clams characterized by a presence of larger individuals across all three species (Figure 9), which is indicative of two potential scenarios. Firstly, recent research using regression-based methods of archaeologically recovered California mussel has established that ancient mussel harvests in Barkley Sound and on the Central Coast were similar in size to modern harvests in areas with a prolonged absence of sea otters (Slade et al. 2022). As sea otters exert significant pressure on various species of shellfish, archaeological evidence has demonstrated that the presence of sea otters in an area will reduce the overall size range of California mussels (Singh et al. 2013). Conversely, in the absence of sea otter predation, California mussels grow faster, live longer, and reach larger overall sizes (ibid.). In this way, predation on shellfish by sea otters in the Broken Group Islands may not have exerted sufficient pressure on clam populations to limit their size range.

Alternatively, intensive human harvesting pressure (i.e., localized resource depression) on shellfish has been thought to produce truncated harvest profiles, by way of reducing the overall size clams are able to reach (Thakar 2011). While the inhabitants of K̲ak̲mak̲imilh actively managed local shellfish populations (Smith et al. 2012), it is less clear whether harvesting pressure was sufficient to reduce the overall size range of clams. In fact, previous work has examined the effects of human harvest pressure on various species of shellfish and observed little change in their abundance or size over time (Butler and Campbell 2004; Daniels

2014; Whitaker 2008). Moreover, ethnographic accounts and oral records point to the active management and exclusion of sea otters from important shellfish harvesting sites (Jackley et al. 2016; Salomon et al. 2020; Salomon et al. 2015).

Therefore, we interpret the size distribution profiles of ancient shellfish harvests at K̲ak̲mak̲imilh to reflect low levels of sea otter predation and sustained human harvesting pressure. Conversely, the truncated size distribution profiles for clams recovered in unit 10 indicate that sea otters may have been present during this earlier period. The increase in size for littleneck and butter clams over time lends support to the idea that sea otters were present early on and later excluded from the area, which would have the effect of releasing the predation pressure on clams. Although, such increases in clam size over time may be occurring irrespective of whether sea otters were present or absent in the area. For instance, the construction of a clam garden, a drop in local sea level, or warmer ocean temperatures could produce similar trends by expanding clam habitat and increasing clam productivity (Toniello et al. 2019).

As an archaeological feature, clam gardens are intertidal rock-walled terraces designed to expand clam habitat thereby enhancing the productivity of numerous shellfish taxa (Deur et al. 2015; Groesbeck et al. 2014; Toniello et al. 2019). Often, clam gardens are located in proximity to village sites and would have served an important role in supporting local food security (Groesbeck et al. 2014). By examining ecological and archaeological clam shell assemblages recovered from Kanish and Waiatt Bays on Quadra Island, BC, Toniello et al. (2019) highlight the integral role clam gardens have had in increasing the growth rate and overall size of butter clams. Indeed, Toniello et al. (2019) reveal similar increases in butter clam size over time, as is documented in this study. Thus, the presence of a clam garden adjacent to the site of

K̲ak̲mak̲imilh (Smith et al. 2012) is likely responsible for the documented increases in littleneck and butter clam size over time.

Sea otters are a major predator to numerous shellfish taxa and would have exerted significant pressure on local shellfisheries in the past (Foster 2021; Salomon et al. 2015). As sea otters exist as keystone predators, they can influence habitat structure leading to long-term ecological consequences (Gregr et al. 2020; Kvitek et al. 1992; Mills et al. 1993; Reisewitz et al. 2006). In order to mitigate the effects of sea otter predation on local community shellfisheries in the past, the inhabitants of K̲ak̲mak̲imilh likely managed otter populations by way of rights-based harvesting restrictions (McKechnie and Wigen 2011; Salomon et al. 2015). Therefore, managing potential threats, such as sea otters, would have been essential for maintaining local food security and fostering social-ecological resilience. These findings challenge contemporary understandings of sea otter carrying capacity in coastal BC, as millennia of interactions between humans and sea otters would have undoubtably shaped the realized niche sea otters historically occupied (Slade et al. 2022).

This study has established a regression-based method for determining the size of littleneck, butter, and horse clams from archaeologically recovered shell fragments. Our findings indicate a strong linear relationship between the dorsal length of clam shells and the length of the hinge and thickness of the umbo (Figure 8). The application of this regression-based method to archaeological samples effectively demonstrates the harvest profile for these historically abundant and culturally important species. The potential this method holds for quantifying the scale of ancient shellfish harvests, and by extension sea otter predation pressure (Foster 2021; Slade et al. 2022), will provide insight into human participation in marine food webs in the deep past throughout the Northwest Coast. To determine the size of ancient clam harvests, historical ecologists can convert size frequency distribution profiles into estimates of harvested biomass using length-to-weight conversion factors (Barber et al. 2012; Bradbury et al. 2005; Foster 2021). Furthermore, researchers will then be able to scale up analyses to understand potential shifts in shellfish biomass at specific sites, while also examining the total biomass of shellfish represented within and across archaeological assemblages. Ultimately, this study presents a methodological approach that has the potential to provide insight into ancient Indigenous shellfisheries and sea otter management practices across the Northwest Coast (following Foster 2021).

3.6 Conclusion

Throughout the Northwest Coast, archaeological assemblages document the enduring and millennia-old relationships between shellfish and Indigenous peoples. Indeed, coastal settlement sites are often comprised of marine shells on a monumental scale (Grier et al. 2017; Letham et al. 2020). As an abundant and readily available food item, littleneck, butter, and horse clams have served an integral role in supporting local food security and fostering resilience for coastal Indigenous communities for millennia (Moss 2011). Yet, to date, comparatively little attention has been directed towards understanding the contribution of biomass shellfisheries provided to coastal Indigenous communities in the deep past (Moss 1993).

This study presents a regression-based methodology for estimating the size profile of ancient clam harvests using ecological and archaeological data. We apply linear regression models to an archaeological dataset at the Tseshaht First Nation village site of K̲ak̲mak̲imilh to estimate ancient Indigenous clam harvest profiles. Size frequency distributions indicate a harvest preference for medium sized clams, although a presence of larger individuals is detected. When size is estimated for each excavation unit (representing different occupation phases of the site), we document a stepwise increase in littleneck and butter clam size over time. Length-to-weight conversion factors were then applied to dorsal length estimates to generate biomass distribution profiles. The right skewed distributions (Figure 9; Figure 10; Figure 11) reveal the presence of large clams across all species, which supports the idea that sea otters were historically excluded from the area. Additionally, the truncated distribution profiles for the unit 10 shellfish assemblage resemble size frequency profiles for shellfish living under prolonged sea otter predation pressure (Kvitek et al. 1992; Slade et al. 2022). One interpretation of these findings is that sea otters were present from 3,000 to 2,000 yr BP, and later excluded from the area after 1,500 yr BP. Alternatively, the documented increases in clam length and biomass over time suggest the construction of a clam garden adjacent to the village site served to expand habitat and increase clam productivity.

The value of this approach lies in its ability to bring ecological insights into conversation with archaeological data, which has the potential to inform contemporary management strategies. For instance, by estimating clam length and biomass distribution profiles we effectively show that the median size of ancient clam harvests at K̲ak̲mak̲imilh closely resemble contemporary size limits outlined by fisheries managers (DFO 2022). Furthermore, the increases in length and biomass detected in littleneck and butter clams over time highlight the resilience of this social-ecological system. Ultimately, this study serves to illuminate Tseshaht peoples’ participation in pre-industrial marine food webs and the role of shellfisheries in fostering community resilience.

Chapter 4: Conclusions

In this chapter, I review each research question described in Chapter 1 and provide context and preliminary answers that are discussed in chapters 2 and 3. Following this, I evaluate how this thesis meets the aspirations outlined in Chapter 1. Additionally, I present a discussion of future research directions required for the adoption of both methodologies that are discussed in chapters 2 and 3. Finally, this chapter concludes with a synthesis of key findings from chapters 2 and 3, while also making linkages to core themes discussed in Chapter 1 (e.g., marine historical ecology and resilience scholarship).

4.1 Review of Research Questions

Questions 1 & 2: ***How can zooarchaeological fisheries data be used to generate estimates of fish and shellfish biomass? What are the steps and sources of uncertainty in generating biomass estimates?***

Throughout this thesis, I have examined how zooarchaeological data can be used to generate estimates of fish and shellfish biomass. In Chapter 2, I presented a method for quantifying the relative composition of fish landings using archaeologically recovered fish remains. Furthermore, by applying ‘Mean Temperature of the Catch’ (MTC) calculations (Cheung et al. 2013) to estimates of fish biomass generated from zooarchaeological data recovered from the sites of Ts’ishaa and Huu7ii, I was able to provide evidence of ocean temperature change, over five millennia. As noted in Chapter 2, these data indicate that coastal Indigenous fisheries reflect cooler ocean temperatures during the mid-Holocene (5,000-3,000 years ago) compared to the late-Holocene (1,800-250 years ago), both of which are cooler than modern catches. Paralleling trends observed in marine sediment core records (Praetorius et al.

2015), these consistent patterns of increasing aMTC suggest long-term ocean warming has occurred since the mid-Holocene.

While aMTC serves as a proxy record for ancient oceanographic temperature variability, the ability to transform MNI observations into probabilistic estimates of fish biomass represents a considerable methodological development in Northwest Coast archaeology. More broadly, the ability to quantitively examine changes in the composition of ancient fish biomass has the potential to expand ecological baselines and inform managers of the scale of ancient fisheries harvests (cf. Fossile et al. 2019). Despite the promise the ‘Palaeothermometer’ approach holds for assessing ancient harvests and quantifying oceanographic variability, numerous sources of uncertainty exist that require further attention. For instance, incorporating uncertainty into body mass estimates is imperative for refining this methodology. As outlined below, this critical next step requires probabilistic modelling, hierarchical Bayesian modelling, and Monte Carlo simulation methods (Yanai et al. 2010) to better incorporate a range of body mass estimates and temperature preferences for each fish taxon. In this way, uncertainty in biomass estimates and aMTC can be improved, which will ultimately strengthen this methodological approach.

In Chapter 3, I presented a regression-based method for estimating the size of fragmentary clam shells using modern measurement data. I then applied these linear regression models to an archaeological dataset to estimate size frequency distribution profiles (i.e., dorsal length, total clam weight, and wet meat weight). The potential this method holds for quantifying the scale of ancient shellfish harvests, and by extension sea otter predation pressure (Foster 2021; Slade et al. 2022), can provide insight into human participation in marine food webs in the deep past. Specifically, by determining size frequency distribution profiles of ancient clam harvests, researchers can convert size profiles into estimates of biomass using length-to-weight conversion factors (Barber et al. 2012; Bradbury et al. 2005; Kvitek et al. 1992). Researchers can then scale up analyses to understand potential shifts in clam biomass at specific sites over time, while also examining total clam biomass represented within and across assemblages. While the methods presented in Chapter 3 exist as an initial step in quantifying harvested clam biomass, this thesis has made efforts to outline future steps required for understanding the role of shellfisheries in Indigenous economies and lifeways.

While both methodologies presented in this thesis involve numerous steps and sources of uncertainty, their ability to estimate the composition of ancient fish catches and calculate the size of past clam harvests effectively documents multiple climatic baselines and harvesting preferences in the northeast Pacific, over the past five millennia. By providing insight into the historical ecology of the region (i.e., climatic variability and sea otter predation pressure), both methods offer perspective on the resilience of local community fisheries in the deep past.

4.2 Review of Research Aspirations

In Chapter 1, I outlined three aspirations to guide and motivate my research. In this section, I provide a discussion of how each aspiration has been addressed in this thesis. For clarity, each aspiration is presented below:

- To emphasize the rich history of relationships between humans and marine systems in the northeast Pacific.
- To examine the resilience of Indigenous fisheries in the deep past.
- To resituate and redefine the role of zooarchaeological data in contemporary fisheries management practices.

My primary research question (*How can zooarchaeological fisheries data be used to generate estimates of fish and shellfish biomass?*) relates to the three aspirations outlined above, as ancient fish and shellfish harvests are evidence of the enduring relationships between Indigenous ancestors and marine social-ecological systems. The two methodological approaches presented in chapters 2 and 3 provide insight into the resilience of past fisheries practices, by drawing upon zooarchaeological data. Importantly, the methods advanced in this thesis reveal new ways of thinking about and working with zooarchaeological data to better understand the reciprocal relationships between Indigenous peoples and marine systems.

The regression-based method for assessing the size of ancient clam harvests has the potential to inform contemporary managers of the various ways in which Indigenous peoples historically managed their shellfisheries. By understanding the role of clam gardens, ancient clam harvesting preferences, and site-specific sea otter management practices, are researchers able to assess the resilience of ancient food systems.

The ‘Palaeothermometer’ approach developed in Chapter 2 represents a novel archaeological method for estimating ancient oceanographic temperature variability using relative biomass estimates from archaeological fish bone assemblages. As coastal archaeological sites with fisheries records are present globally, the research methodology advanced in Chapter 2 illuminates the potential for detecting shifts in fisheries from various locations and timescales. Indeed, the contribution developed in Chapter 2 is a promising method for assessing the resilience of local fisheries to changes in ocean temperature. By extending the baseline on ancient oceanographic conditions, we document how these conditions may differ from today. In fact, the findings discussed in Chapter 2 reveal that while ancient Indigenous fisheries have persisted for millennia, current conditions are unprecedented.

In these ways, the methods developed in Chapter 2 and Chapter 3 align closely with the three research aspirations. Firstly, by demonstrating millennia-old relationships between local fisheries and the communities of Huu7ii, Ts'ishaa, and Kakmakimilh. Secondly, the resilience of fisheries in the face of climatic variability. And finally, the role of zooarchaeological data in extending both climatic baselines and catch records.

4.3 Future Directions

The Palaeothermometer Approach

As noted in Chapter 2, the 'Palaeothermometer' approach for estimating millennial-scale changes in ocean temperature represents the first application of the MTC method to preindustrial fisheries records using archaeological data. As coastal archaeological sites with fisheries records are present across the globe, this research methodology illuminates the potential for detecting shifts in fisheries from various locations and timescales. However, this method involves several assumptions and sources of uncertainty suitable for future refinement. A substantive consideration relates to the accuracy of MTC as a temperature proxy, as well as the temporal resolution of archaeological data that spans millennial time scales. While there is no doubt such detrended temperature estimates incorporate a range of climatic states, such time-averaged data also serves to reduce the potential confounding effects of fishing effort, seasonality in site use, fishing technology, and variability in climate. As the data reported on here reflect Indigenous communities living on small islands and consuming fish on a regular basis, changes in the mode of fishing over time may be independent of changing ocean temperature.

To better account for the uncertainty and variability in our biomass and aMTC estimates, uncertainty could be propagated throughout the calculations. For instance, this could be done with hierarchical Bayesian methods and Monte Carlo simulations (Yanai et al. 2010), whereby specified prior distributions could be associated with each estimated parameter and its associated uncertainty. In other words, body mass distributions for each species could be used to inform biomass estimates improving on the median, 25th and 75th empirical quartiles. Applying hierarchical Bayesian methods to simulate potential scenarios, I would be able to estimate the uncertainty around biomass and aMTC results. Following Cheung et al. (2013), I could then use a generalized additive mixed effect model (GAMM) to compare a larger number of archaeological sites across the BC coast, while simultaneously factoring in the effects of latitude and fishing effort. Furthermore, such a modelling approach could draw upon other proxy records of ocean temperature to compare to aMTC results, such as marine sediment core and stable oxygen isotope data.

Clam Biomass Estimations

As presented in Chapter 3, the regression-based method for determining the size of clams from fragmentary remains has the potential to inform researchers of ancient harvest profiles. Such a method for assessing ancient clam harvests and the effects of sea otter predation will serve to inform managers of cultural practices that fostered resilience and adaptive capacity within local shellfisheries. Future efforts require measuring clams recovered from other archaeological assemblages to then back-cast ancient size distribution profiles. Considering that clam shells are abundant and ubiquitous in coastal archaeological sites, this method has significant potential in contemporary management efforts.

4.4 A Holocene Perspective of Fisheries in the Northeast Pacific

Assessing the Resilience of Ancient Indigenous Fisheries

This thesis has examined the enduring role of fisheries in supporting the well-being of coastal Indigenous peoples in the northeast Pacific, over the past five millennia. Drawing upon the frameworks of marine historical ecology and resilience theory, the findings presented in Chapter 2 and Chapter 3 are now discussed in the following section.

In Chapter 2, we presented the 'Palaeothermometer' approach for estimating the composition of ancient fish catches at two Indigenous settlement sites in Barkley Sound. The results of this study are based on previously analysed zooarchaeological data (McKechnie 2005a; McKechnie 2012), which indicate that the relative proportion of fish landings reflect modest differences between the villages of Ts'ishaa and Huu7ii. As noted in Chapter 2, we interpret modest differences in fish landings to reflect both the local habitat characteristics in proximity to each village, as well as social and cultural histories associated with these politically separate communities. While the composition of fish landings and aMTC results differ between sites, the findings presented in Chapter 2 reveal coherent and similar trends of increasing ocean temperature over the past 5,000 years. Collectively, these results indicate that the fisheries at Ts'ishaa and Huu7ii endured over five millennia despite substantial oceanographic variability. Such an approach to assessing the scale of ancient fisheries and how Indigenous ancestors responded to variability in oceanographic conditions is urgently needed in fisheries management practices today (Kittinger et al. 2015).

The 'Palaeothermometer' approach advanced in Chapter 2 serves to highlight the resilience of local community fisheries in Barkley Sound over five millennia. Importantly, this approach has the potential to broaden contemporary fisheries management practices, by increasing the relevance of zooarchaeological data. Converting zooarchaeological data into estimates of fish biomass has been limited to date (although see Fossile et al. 2019), which is largely due to the substantial methodological considerations required. The work presented in Chapter 2 serves to translate previously incomparable data into a metric that is readily applicable to fisheries management practices today.

Currently, researchers are unsure of the full range of ecological impacts that ancient shellfish aquaculture practices had on social-ecological systems throughout the northeast Pacific. Previous work has examined the effects of human harvest pressure on various species of shellfish and observed little change in the abundance or size of shellfish over time (Butler and Campbell 2004; Daniels 2014; Whitaker 2008). Such observations are in contrast to other studies, which indicate that under intense harvesting pressure clams are not able to grow to large sizes (Thakar 2011). The findings presented by Butler and Campbell (2004), Daniels (2014), and Whitaker (2008) amongst others indicate a lack of evidence for localized resource depression.

The regression-based method developed in Chapter 3 has the potential to refine current understandings of the scale of ancient shellfish harvests, while also considering shell size as a measure of sea otter predation pressure in the past. As demonstrated in this study, by applying linear regression models to archaeological samples, researchers can effectively measure the size profile for these historically abundant and culturally important shellfish taxa (Singh and McKechnie 2015; Slade et al. 2022). Converting size frequency distribution profiles into estimates of shellfish biomass (e.g., total clam weight and wet meat weight) also provides a metric for assessing changes in the size and scale of ancient clam harvests as well as relative food use.

As sea otters exist as keystone predators (Foster et al. 2021), their rapid recolonization of coastlines throughout the northeast Pacific poses a serious threat to the food security of coastal Indigenous communities (Burt et al. 2020; Pinkerton et al. 2019). Therefore, assessing the harvest profile of clams can offer insight into the presence or absence of predatory sea otters, and by extension, the degree to which people managed otter populations in the past (Foster 2021; Slade et al. 2022). By understanding the cross-scale interactions between clam growth patterns

(Jackley et al. 2016; Toniello et al. 2019), the habitat characteristics of clam gardens (Groesbeck et al. 2014), human harvest pressure (Daniels 2014; Whitaker 2008), and sea otter abundance (Foster 2021; Slade et al. 2022), researchers will be able to provide long-term insight into the adaptive capacity and resilience of ancient aquaculture practices in the northeast Pacific.

Fisheries as Social-Ecological Systems

Although Indigenous communities in the northeast Pacific have been classically described as ‘hunter-gatherers’ or ‘fisher-hunter-gatherers,’ they maintained disproportionately high population densities, extensive trade networks, and elaborate territorial and governance structures with a corresponding influence on coastal landscapes (Moss 2011). Together, oral history, ethnographic accounts, and archaeology has informed researchers of the sustained use and management of marine and terrestrial resources by both Tseshaht and Huu-ay-aht peoples, over the last five millennia (McKechnie 2015; McMillan and St. Claire 2005; McMillan and St. Claire 2012). Currently, researchers are working to understand the ecological impacts of ancient shellfisheries in Barkley Sound, and how these social-ecological systems responded to change.

Archaeological work in Barkley Sound has contributed valuable insight into Tseshaht and Huu-ay-aht peoples’ participation in historic food webs and variability in past ecological conditions. In Barkley Sound, village sites contain abundant faunal remains, representing numerous marine and terrestrial taxa used by people (McMillan et al. 2008; McMillan and St. Claire 2005; McMillan and St. Claire 2012). These findings help illuminate Tseshaht and Huu-ay-aht peoples’ participation in pre-industrial marine food webs and the long-term role of fisheries in Indigenous economies and lifeways.

While Tseshaht and Huu-ay-aht First Nations’ use of seasonal and offshore marine resources (i.e., forage fish, salmon, whale (*Mysticeti* spp.), and northern fur seal (*Callorhinus* *ursinus*)) is well documented (Hillis et al. 2020; McKechnie 2014; McKechnie et al. 2014; McMillan et al. 2008; Moss et al. 2006; Newsome et al. 2007), shellfish – an abundant and readily available food item – has received significantly less attention (Moss 1993). As Moss (1993) argues, this may be due to a "lack of ethnographic attention to Northwest Coast shellfishing compared to the more dramatic, technologically complex, and male-dominated activities of fishing and sea mammal hunting". To date, little work has been done on quantifying the total biomass of shellfish represented in archaeological deposits throughout Barkley Sound. In this way, researchers remain unsure of the scale of shellfish harvests in the region and how shellfish contributed to ancient Indigenous economies.

While the history of shellfish harvests in Barkley Sound is a relatively unexamined field of inquiry, oral history, ethnographic data (McMillan and St. Claire 2005:32-33), and archaeological evidence document the sustained use of shellfish as a reliable food source for millennia (e.g., Efford 2019; Monks 2017; Sumpter 2005). Throughout the region, California mussels, butter, and littleneck clams make up large proportions of archaeological deposits and date back to the earliest sites with preserved fauna (McKechnie 2014; McMillan and St. Claire 2005; McMillan and St. Claire 2012; Sumpter et al. 2005).

Maintaining clam gardens was a sustained practice that contributed to a village's overall food security and represents an adaptive strategy of ecosystem engineering (Groesbeck et al. 2014). Often, clam gardens are located in proximity to village sites and would have served an important role in supporting local food security, by way of expanding habitat and enhancing shellfish productivity (Deur et al. 2015; Groesbeck et al. 2014; Toniello et al. 2019). The establishment of elaborate governance systems to provide access and stewardship rights was essential for maintaining clam garden infrastructure so as to enhance bivalve production (Jackley et al. 2016). Furthermore, this management system represents an adaptive strategy, as it enhances local food security through controlled access rights. These multiple lines of evidence speak to the dynamic nature of relations that give structure to the social-ecological system in which local fisheries are enmeshed.

4.5 Closing Thoughts

Currently, there is an urgent need for a more integrated perspective on the ways in which humans modify and shape social-ecological systems, as certain practices can hold adaptive benefits or long-term consequences. Collectively, humans have now had significant and lasting impacts on global landscapes and seascapes (Armstrong et al. 2017; Boivin et al. 2016; Brewer and Riede 2018; Jackson et al. 2001; Steneck and Pauly 2019; Zeder 2018). Humans must now reconcile with past decisions and practices, while engineering new (and old) adaptive strategies to remain resilient to future change.

As an applied field of research, historical ecology can inform managers of past environmental conditions and the potential consequences of historic niche constructing activities (Armstrong et al. 2017; Boivin et al. 2016). Utilizing archaeological methods, researchers can provide insight into past cultural practices that lead to “sustainable (adaptive) or unsustainable (maladaptive) constellations” (Brewer and Riede 2018). In this way, historical ecology applied to archaeological assemblages can provide insight into past strategies that served to manage and respond to oceanographic variability. As First Nation peoples increasingly assert their rights to self-governance and implement resource management policies of their own, this presents an opportunity for the integration of resilient practices and management strategies.

Drawing upon a historical-ecological approach, this thesis has explored the enduring role of local fisheries in supporting the well-being of Indigenous communities in the northeast

Pacific, over the past five millennia. In this thesis, I advance the development and application of two methodologies for 1) quantifying the composition of ancient fish landings, 2) estimating ancient ocean temperatures from archaeological fish bone assemblages, and 3) assessing the ancient harvest profile of shellfish using a regression-based approach. Together, these methods offer a long-term perspective on the enduring relationships between Indigenous peoples and marine environments in the northeast Pacific. Ultimately, I hope these insights will contribute towards fostering ecologically sustainable and socially just operating space for Canada's Pacific fisheries.

Appendix A: Supplementary Information for Chapter 2

5.1 Supplementary Information: Tables

Table 13 Taxonomic categories of fish used to derive biomass and aMTC estimates, including the species or genera comprising each category, the weighted body mass (kg) for the 25th (Low), 50th (Mid) and 75th (High) empirical quartiles, the weighted median temperature preference (°C; from www.fishbase.org), the sample size (*n*), and the references for body mass estimates.

Categories[1]	**Species or Genera**	**Low (kg)**	**Mid (kg)**	**High (kg)**	**Temp. Pref. (°C)**	***n***	**References**
Anchovy	*Engraulis mordax*$^{\mathbf{D}}$	0.019	0.021	0.023	11.3	6	McKenzie (2021)
Clingfish	*Gobiesox maeandricus*$^{\mathbf{D}}$	0.01	0.011	0.014	13.1	4	McKenzie (2021)
Dogfish	*Squalus suckleyi*$^{\mathbf{I}}$	0.912	1.25	1.778	11.2	3,331	Anderson et al. (2019)
Flatfish	*Eopsetta jordani*$^{\mathbf{I}}$, *Lepidopsetta bilineata*$^{\mathbf{I}}$, *Microstomus pacificus*$^{\mathbf{I}}$, *Platichthys stellatus**$^{\mathbf{D}}$	0.356	0.569	0.867	4.7	17,025	Anderson et al. (2019); DFO (2001)*
Gadids	*Gadus macrocephalus*$^{\mathbf{I}}$, *Microgadus proximus*$^{\mathbf{I}}$	0.182	0.345	0.638	5.5	7,217	Anderson et al. (2019)
Greenling	*Hexagrammos decagrammus*$^{\mathbf{D}}$, *H. stelleri*$^{\mathbf{D}}$	0.169	0.303	0.529	4.5	83	McKechnie (2007a); McKechnie (2007b)
Gunnel	*Apodichthys flavidus*$^{\mathbf{D}}$, *Pholis laeta*$^{\mathbf{D}}$	0.007	0.011	0.024	9.8	12	McKenzie (2021)
Hake	*Merluccius productus*$^{\mathbf{I}}$	0.094	0.63	0.869	9.8	2,349	Anderson et al. (2019)
Halibut	*Hippoglossus stenolepis*$^{\mathbf{D}}$	4.399	7.567	13.362	3.0	1,016	Salmen-Hartley (2018)
Herring	*Clupea pallasii*$^{\mathbf{D}}$	0.088	0.112	0.143	5.0	75,259	DFO (2015); Sanchez (2020)
Lingcod	*Ophiodon elongatus*$^{\mathbf{I}}$	1.085	2.408	3.689	6.6	2,993	Anderson et al. (2019)
Mackerel	*Pleurogrammus monopterygius*$^{\mathbf{D}}$	0.455	0.76	0.915	3.4	89	McKenzie (2021)
Midshipman	*Porichthys notatus*$^{\mathbf{D}}$	0.037	0.064	0.07	11.9	5	McKenzie (2021)
Perch	*Cymatogaster aggregate*$^{\mathbf{D}}$, *Rhacochilus vacca*$^{\mathbf{D}}$	0.395	0.475	0.700	11.8	40	McKenzie (2021); Vigneron (2021)
Prickleback	*Anoplarchus purpurescens*$^{\mathbf{D}}$, *Lumpenus sagitta*$^{\mathbf{D}}$,	0.008	0.01	0.014	8.6	27	McKenzie (2021)

	Xiphister atropurpureus^{D}, *Xiphister mucosus*^{D}						
Ratfish	*Hydrolagus colliei*^{I}	0.27	0.455	0.558	7.4	1,673	Anderson et al. (2019)
Rockfish[2] (*Sebastes* spp.)	*S. melanops*^{D}, *S. mystinus*^{D}, *S. pinniger*^{D}, *S. nebulosus*^{D}, *S. caurinus*^{D}, *S. maliger*^{D}, *S. proriger*^{D}, *S. brevispinis*^{D}, *S. flavidus*^{D}, *S. nigrocinctus*^{D}, *S. entomelas*^{D}, *S. ruberrimus*^{D}	0.243	0.556	0.911	6.9	129	McKechnie (2014)
Sablefish	*Anoplopoma fimbria*^{D}	0.358	0.403	0.546	3.5	36	Nims and Butler (2019)
Salmon[3] (*Oncorhynchus* spp.)	Weighted Salmon: *O. gorbuscha*^{D}, *O. keta*^{D}, *O. kisutch*^{D}, *O. nerka*^{D}, *O. tshawytscha*^{D}	3.523	4.308	5.399	4.6	16,045,020	NPAFC (2021)
	Large Salmon: *O. keta*^{D}, *O. tshawytscha*^{D}	4.26	4.71	5.878	4.5	9,628,390	NPAFC (2021)
	Medium Salmon: *O. gorbuscha*^{D}, *O. keta*^{D}, *O. kisutch*^{D}, *O. nerka*^{D}, *O. tshawytscha*^{D}	2.18	3.584	4.533	4.7	16,045,020	NPAFC (2021)
	Small Salmon: *O. gorbuscha*^{D}, *O. kisutch*^{D},	1.716	2.367	3.575	4.9	944,750	NPAFC (2021)
Sand Lance	*Ammodytes hexapterus*^{D}	0.001	0.002	0.002	4.7	9	McKenzie (2021)
Sculpin[4]	*Enophrys bison*^{D}, _Hemilepidotus hemilepidotus_*^{D}, _Scorpaenichthys marmoratus_**^{D}	1.297	1.322	1.603	6.2	24	McKenzie (2021); McKechnie (2007a)*; McKechnie (2007b)*; DFO (2001)**
Skate	*Bathyraja interrupta*^{I}, *Beringraja binoculata*^{I}, *Beringraja rhina*^{I}	0.909	2.244	4.971	5.7	571	Anderson et al. (2019)
Smelt	*Hypomesus pretiosus*^{D}, *Mallotus villosus*^{D}, _Thaleichthys pacificus_*	0.028	0.037	0.037	4.6	125	McKenzie (2021); Anderson et al. (2019)*

Wolf eel	*Anarrhichthys ocellatus*^{I}	1.84	3.115	4.39	5.9	2	Anderson et al. (2019)

1. Taxonomic categories are weighted based on the proportion of individual archaeological specimens identified to species level (% MNI) for the Barkley Sound study region (McKechnie and Moss 2016). When such data was not available, we calculated proportionality based on aDNA analysis of archaeological specimens (Rodrigues et al. 2018), vertebral measurements of archaeological specimens, relative proportions of species caught in the fisheries independent bottom trawl surveys on western Vancouver Island (e.g., Anderson et al. 2019), and locally obtained species in the University of Victoria's Zooarchaeology Comparative Collection (McKenzie 2021).
2. Rockfish species proportionality based on Rodrigues et al. (2018), which was used to generate a weighted median temperature preference for the taxonomic category of rockfish. Body mass estimates were obtained using length-to-weight conversion factors for measurements of archaeological specimens (McKechnie 2007a; McKechnie 2007b; Orchard 2003).
3. Salmon species proportionality is based on transverse vertebral diameter measurements of archaeological specimens (following Cannon and Yang 2006; Cannon and Yang 2011; Huber et al. 2011; Miszaniec 2021; Moss et al. 2014; Orchard 2003; Orchard and Szpak 2011). The body mass of salmon is calculated using the proportionality of small (<8.0 mm), medium (8.0-10.5 mm) and large (>10.5 mm) vertebrae where the body mass of each species of salmon is a combination of Pink (*Oncorhynchus gorbuscha*) and Coho (*Oncorhynchus kisutch*) (small), all species (medium) and Chum (*Oncorhynchus keta*) and Chinook (*Oncorhynchus tshawytscha*) (large) based on fisheries dependent catch spanning from 1996 to 2019 (NPAFC 2021).
4. Sculpin species proportionality is based on the relative proportion of the 'Minimum Number of Individuals' (MNI) identified to species level (% MNI).

Note: the symbols **D** and **I** represent the type of fisheries data that was used to generate body mass estimates. **D** refers to fisheries dependent data (e.g., commercial, recreational, subsistence landings, and archaeological catches), while **I** refers to fisheries independent data (e.g., systematic scientific survey).

Table 14 Fine screen (3.2 and 2 mm) column sample vertebrate data used in this study are from two archaeological sites, DfSi-16 (Ts'ishaa) and DfSh-7 (Huu7ii), as described in McKechnie (2005a; 2012) and with archeological context further reported in McMillan and St. Claire (2005; 2012). Included in this table are site name, column sample name, approximate age range of each column sample, individual levels examined for faunal analysis, the total volume (L) of sediment recovered, and the total 'Number of Identified Specimens' (NISP) per column sample. Note, the NISP for DfSi-16 and DfSh-7 present data for fish only (i.e., excluding mammal, bird, and unidentified specimens).

Site Name	Column Sample	Approx. Age (cal yr BP)	No. of Examined Levels	Total Volume (litres)	NISP
DfSi-16	N2-4/W102-104	1,500-250	10	40	2,857
DfSi-16	S14-16/W25-27	1,800-250	12	75	1,928
DfSi-16	S5-7/W11-13	1,000-250	12	24	941
DfSi-16	S56-57/W50-52	5,000-3,000	13	13	558
DfSi-16	S62-64/W62-64	5,000-3,000	5	20	695

DfSh-7	N10-12/E2-4	1,500-400	19	19	2,928
DfSh-7	N12-14/E6-8	1,500-400	12	12	2,406
DfSh-7	N18-20/E2-4	1,500-400	21	21	4,510
DfSh-7	N18-20/E6-8	1,500-400	21	21	8,507
DfSh-7	N10-12/E4-6	1,500-400	1	1	99
DfSh-7	N14-16/E15.5-16	1,500-400	6	6	1,730
DfSh-7	N18-20/E15.5-16	1,500-400	8	8	1,551
DfSh-7	N18-20/E26-28	1,500-400	9	9	1,790
DfSh-7	N18-20/E34-36	1,500-400	25	25	6,980
DfSh-7	N2-4/W18-20	5,000-3,000	25	25	11,439
DfSh-7	N4-6/E0-2	4,700-3,000	17	34	5,920

Table 15 Selection hierarchy for estimating the body mass of each species of fish present in the Barkley Sound zooarchaeological record.

Rank	Source Type	Sources
1	Measured archaeological specimens with body mass estimated from length-to-weight regression formulae	McKechnie 2007a; McKechnie 2007b; Nims and Butler 2019; Orchard 2003; Salmen-Hartley 2018; Sanchez 2020; Vigneron 2021
2	Regionally specific fisheries independent scientific survey data	Anderson et al. 2019
3	Recreational length and weight data for dockside landings in Barkley Sound (Areas 23 and 123)	DFO 2001
4	Size and body mass data for specimens in the University of Victoria Zooarchaeology Comparative Collection	McKenzie 2021
5	Other archaeological and scientific literature	NPAFC 2021

Table 16 Radiocarbon results for archaeological deposits associated with column sample data used in this study. Calibrated age-ranges are in calendar years before present (BP) at 2-sigma probability (95.4%) and were calibrated with Oxcal (Ramsey 2009) using the Intcal20 curve (Reimer et al. 2020).

Site No.	Sample No.	Material	14C Age (BP)	Calibrated Age-Range	Source
DfSi-16	Beta-134655	Charcoal	1490±60	1517-1296	1
DfSi-16	Beta-134656	Charcoal	1800±60	1830-1545	1
DfSi-16	Beta-147071	Charcoal	3580±80	4141-3645	1
DfSi-16	Beta-147072	Charcoal	500±60	648-335	1
DfSi-16	Beta-147073	Charcoal	5050±60	5916-5608	1
DfSi-16	Beta-147074	Charcoal	1230±90	1295-961	1
DfSi-16	Beta-147075	Charcoal	690±60	723-552	1
DfSi-16	Beta-158739	Charcoal	430±60	545-315	1
DfSi-16	Beta-158740	Charcoal	3000±70	3365-2968	1
DfSi-16	Beta-158741	Charcoal	4470±70	5309-4877	1
DfSi-16	Beta-158742	Charcoal	3330±70	3817-3396	1

DfSi-16	Beta-158743	Charcoal	4430±80	5294-4861	1
DfSi-16	Beta-158744	Charcoal	3050±70	3442-3009	1
DfSi-16	Beta-158745	Charcoal	4080±70	4822-4420	1
DfSi-16	Beta-158746	Charcoal	1620±60	1692-1374	1
DfSi-16	Beta-158747	Charcoal	4160±70	4849-4450	1
DfSh-7	Beta-195633	Charcoal	640±50	670-548	2
DfSh-7	Beta-195634	Charcoal	740±70	788-554	2
DfSh-7	Beta-195635	Charcoal	470±60	630-320	2
DfSh-7	Beta-195636	Charcoal	820±60	905-662	2
DfSh-7	Beta-195637	Charcoal	3190±60	3561-3250	2
DfSh-7	Beta-195638	Charcoal	1170±70	1271-936	2
DfSh-7	Beta-195639	Charcoal	1330±50	1344-1128	2
DfSh-7	Beta-195640	Charcoal	1560±60	1546-1311	2
DfSh-7	Beta-195641	Charcoal	4280±70	5046-4580	2
DfSh-7	Beta-195642	Charcoal	1230±60	1288-994	2
DfSh-7	Beta-221950	Charcoal	610±40	657-541	2
DfSh-7	Beta-221951	Charcoal	410±70	540-310	2
DfSh-7	Beta-221952	Charcoal	370±70	523-297	2
DfSh-7	Beta-221953	Charcoal	2830±60	3145-2781	2
DfSh-7	Beta-221954	Charcoal	1190±60	1269-960	2
DfSh-7	Beta-221955	Charcoal	710±40	722-561	2
DfSh-7	Beta-221956	Charcoal	1290±70	1342-1059	2
DfSh-7	Beta-221957	Charcoal	670±70	723-540	2
DfSh-7	Beta-221959	Charcoal	990±50	1046-752	2
DfSh-7	Beta-221960	Charcoal	3690±70	4236-3840	2
DfSh-7	Beta-221961	Charcoal	710±60	731-554	2
DfSh-7	Beta-221962	Charcoal	3810±50	4406-4014	2
DfSh-7	Beta-221963	Charcoal	3810±80	4419-3978	2
DfSh-7	Beta-236288	Charcoal	1060±40	1064-911	2
DfSh-7	Beta-236289	Charcoal	920±50	923-731	2
DfSh-7	CAMS-28075	Charcoal	2260±50	2352-2146	2
DfSh-7	CAMS-97176	Charcoal	3585±40	4060-3724	2
DfSh-7	CAMS-97177	Charcoal	3735±35	4231-3977	2
DfSh-7	CAMS-97181	Charcoal	4210±35	4851-4620	2
DfSh-7	CAMS-97182	Charcoal	4415±35	5275-4865	2
DfSh-7	CAMS-97186	Charcoal	3100±35	3390-3215	2
DfSh-7	CAMS-97191	Charcoal	350±45	495-310	2
DfSh-7	CAMS-97197	Charcoal	1310±35	1296-1176	2
DfSh-7	CAMS-97198	Charcoal	1230±35	1270-1065	2
DfSh-7	CAMS-97203	Charcoal	1385±35	1354-1179	2
DfSh-7	CAMS-97204	Charcoal	1300±35	1296-1154	2

Note: source 1 refers to original radiocarbon data for DfSi-16 presented in McMillan and St. Claire (2005), while source 2 refers to radiocarbon data for DfSh-7 as presented in McMillan and St. Claire (2012).

Table 17 Comparison of the relative proportion of the ‘Minimum Number of Individuals’ (% MNI) and the relative proportion of the catch (% Biomass) for each archaeological site and temporal period under consideration. % Biomass is calculated using the 25th quartile body mass estimate multiplied by MNI counts for each taxonomic grouping.

	Ts’ishaa % MNI		**Ts’ishaa % Biomass**		**Huu7ii % MNI**		**Huu7ii % Biomass**	
Approx. Age (cal yr BP)	5,000-3,000	1,800-250	5,000-3,000	1,800-250	5,000-3,000	1,500-400	5,000-3,000	1,500-400
Anchovy	7	16	<1	1	7	13	<1	<1
Dogfish	3	4	4	6	3	6	9	9
Flatfish	2	2	1	1	<1	3	<1	2
Greenling	24	13	7	4	11	12	5	3
Hake	<1	3	<1	<1	<1	6	<1	1
Halibut	4	2	25	15	<1	<1	3	2
Herring	27	23	4	4	62	28	15	4
Lingcod	5	4	9	7	<1	2	1	3
Perch	10	7	7	5	5	3	5	2
Ratfish	1	1	<1	1	1	1	1	1
Rockfish	11	13	5	5	4	10	3	4
Sablefish	1	2	1	1	<1	3	<1	2
Salmon	6	7	36	41	6	10	57	60
Sculpin	<1	4	<1	10	1	3	2	7

Table 18 Comparison of the relative proportion of the ‘Minimum Number of Individuals’ (% MNI) and the relative proportion of the catch (% Biomass) for each archaeological site and temporal period under consideration. % Biomass is calculated using the 75th quartile body mass estimate multiplied by MNI counts for each taxonomic grouping.

	Ts’ishaa % MNI		**Ts’ishaa % Biomass**		**Huu7ii % MNI**		**Huu7ii % Biomass**	
Approx. Age (cal yr BP)	5,000-3,000	1,800-250	5,000-3,000	1,800-250	5,000-3,000	1,500-400	5,000-3,000	1,500-400
Anchovy	7	16	<1	<1	7	13	<1	<1
Dogfish	3	4	3	6	3	6	9	9
Flatfish	2	2	1	2	<1	3	<1	3
Greenling	24	13	9	5	11	12	9	5
Hake	<1	3	<1	2	<1	6	<1	5
Halibut	4	2	32	21	<1	<1	4	3
Herring	27	23	3	3	62	28	14	3
Lingcod	5	4	13	11	<1	2	1	5
Perch	10	7	5	4	5	3	5	2
Ratfish	1	1	<1	1	1	1	1	1
Rockfish	11	13	7	9	4	10	6	8
Sablefish	1	2	<1	1	<1	3	<1	1
Salmon	6	7	23	30	6	10	49	48
Sculpin	<1	4	<1	6	1	3	2	5

Work Cited

Allen CR, Angeler DG, Chaffin BC, Twidwell D, Garmestani A, Sveriges l (2019) Resilience reconciled. Nat. Sustain. 2(10):898-900 https://doi.org/10.1038/s41893-019-0401-4

Anderson L, Abbott MB, Finney BP, Burns SJ (2007) Late Holocene moisture balance variability in the southwest Yukon Territory, Canada. Quat. Sci. Rev. 26(1):130-141 https://doi.org/10.1016/j.quascirev.2006.04.011

Anderson SC, Keppel EA, Edwards AM (2019) A reproducible data synopsis for over 100 species of British Columbia groundfish. Fisheries and Oceans Canada, Nanaimo.

Angeler DG, Allen CR, Sveriges I (2016) Quantifying resilience. J. Appl. Ecol. 53(3):617-624 https://doi.org/10.1111/1365-2664.12649

Armstrong CG, Shoemaker AC, McKechnie I, Ekblom A, Szabó P, Lane PJ, McAlvay AC, Boles OJ, Walshaw S, Petek N, Gibbons KS, Morales EQ, Anderson EN, Ibragimow A, Podruczny G, Vamosi JC, Marks-Block T, LeCompte JK, Awasis S, Nabess C, Sinclair P, Crumley CL (2017) Anthropological contributions to historical ecology: 50 questions, infinite prospects. PloS One 12(2):e0171883

Asch M (2002) From Terra Nullius to Affirmation: Reconciling Aboriginal Rights with the Canadian Constitution. Canadian Journal of Law and Society 17(2):23-39 https://doi.org/10.1017/S0829320100007237

Atleo ER (2004) Tsawalk: a Nuu-chah-nulth worldview. UBC Press, Vancouver

Balée W (1998) Historical ecology: premises and postulates. In: Balée W (ed) Advances in Historical Ecology, Columbia University Press, New York, pp 13-29

Balée W (2006) The research program of historical ecology. Annu. Rev. of Anthropol. 35(1):75-98

Barber JS, Mitchell T, Gibson J, Hoyopatubbi T, Gobert T, Ferderer A (2012) Clam population variability within a Puget Sound bivalve management region. Swinomish Indian Tribal Community Technical Report SWIN-TR-2012-01

Baumgartner T (1992) Reconstruction of the history of the Pacific sardine and northern anchovy populations over the past two millenia from sediments of the Santa Barbara basin, California. CalCOFI Rep. 33(1):24-40

Beller E, McClenachan L, Trant A, Sanderson EW, Rhemtulla J, Guerrini A, Grossinger R, Higgs E (2017) Toward principles of historical ecology. Am. J. Bot. 104(5):645-648 https://doi.org/10.3732/ajb.1700070

Berkes F, Folke C, Colding J (2000) Linking social and ecological systems: management ractices and social mechanisms for building resilience. Cambridge University Press

Berkes F, Turner NJ (2006) Knowledge, learning and the evolution of conservation practice for social-ecological system resilience. Hum. Ecol. 34(4):479-494

Biggs R, Schlüter M, Biggs D, Bohensky EL, BurnSilver S, Cundill G, Dakos V, Daw TM, Evans LS, Kotschy K, Leitch AM, Meek C, Quinlan A, Raudsepp-Hearne C, Robards MD, Schoon ML, Schultz L, West PC (2012) Toward Principles for Enhancing the Resilience of Ecosystem Services. Annu. Rev. Environ. Resour. 37(1):421-448 https://doi.org/10.1146/annurev-environ-051211-123836

Boivin NL, Zeder MA, Fuller DQ, Crowther A, Larson G, Erlandson JM, Denham T, Petraglia MD (2016) Ecological consequences of human niche construction: Examining long-term anthropogenic shaping of global species distributions. PNAS 113(23):6388-6396

Boyd RT (1999) Indians, fire, and the land in the Pacific Northwest. Oregon State University Press, Corvallis, Oregon

Bradbury A, Blake B, Speckand C, Rogers D (2005) Length-weight models for intertidal clams in Puget Sound. Washington Department of Fish and Wildlife, Washington

Braje TJ, Rick TC, Szpak P, Newsome SD, McCain JM, Smith EAE, Glassow M, Hamilton SL (2017) Historical ecology and the conservation of large, hermaphroditic fishes in Pacific Coast kelp forest ecosystems. Sci. Adv. 3(2):e1601759 https://doi.org/10.1126/sciadv.1601759

Brewer J, Riede F (2018) Cultural heritage and climate adaptation: a cultural evolutionary perspective for the Anthropocene. World Archaeol. 50(4):554-569

Brown F, Brown YK (2009) Staying the course, staying alive: coastal First Nations fundamental truths: biodiversity, stewardship and sustainability. Biodiversity BC, Victoria.

Burt JM, Kii’iljuss BW, Malchoff T, Wii-tsts-koom AM, Skil Hiilans AD, Gitkinjuass, Salomon AK (2020) Enabling Coexistence: Navigatingn predator-induced regime shifts in human-ocean systems. People and Nature 2(3):557-574 https://doi.org/10.1002/pan3.10090

Butler VL, Campbell SK (2004) Resource intensification and resource depression in the Pacific Northwest of North America: A zooarchaeological review. J. World Prehist. 18(4):327-405

Caldwell ME, Lepofsky D, Combes G, Washington M, Welch JR, Harper JR (2012) A bird's eye view of Northern Coast Salish intertidal resource management features, southern British Columbia, Canada. J. Isl. Coast. Archaeol. 7(2):219-233

Campbell B, Braje TJ (2015) Estimating California mussel (*Mytilus californianus*) size from hinge fragments: a methodological application in historical ecology. J. Archaeol. Sci. 58(1):167-174

Cannon A, Burchell M, Bathurst R (2008) Trends and strategies in shellfish gathering on the Pacific Northwest Coast of North America. Early Human Impact on Megamolluscs:7-22

Cannon A, Yang DY (2006) Early Storage and Sedentism on the Pacific Northwest Coast: Ancient DNA Analysis of Salmon Remains from Namu, British Columbia. Am. Antiq. 71(1):123-140 https://doi-org.ezproxy.library.uvic.ca/40035324

Cannon A, Yang DY (2011) Pushing limits and finding interpretive balance: A reply to Monks and Orchard. Am. Antiq. 76(3):585-595

Carney M, Tushingham S, McLaughlin T, d'Alpoim Guedes J (2021) Harvesting strategies as evidence for 4000 years of camas (*Camassia quamash*) management in the North American Columbia Plateau. R. Soc. Open Sci. 8(4):202213-202213 https://doi.org/10.1098/rsos.202213

Chavez FP, Ryan J, Lluch-Cota SE, Niquen CM (2003) From Anchovies to Sardines and Back: Multidecadal Change in the Pacific Ocean. Science 299(5604):217-221 https://doi.org/10.1126/science.1075880

Cheung WWL, Watson R, Pauly D (2013) Signature of ocean warming in global fisheries catch. Nature 497(7449):365-368 https://doi.org/10.1038/nature12156

Claxton E, Elliott J Sr. (1994) Reef net technology of the Saltwater people, Saanich Indian School Board, Brentwood Bay

Croes D (1992) Exploring Prehistoric Subsistence Change on the Northwest Coast. In: Croes D, Hawkins R, Isaac B (eds) Long-Term Subsistence Change in Prehistoric North America. JAI Press, Greenwich, p 337-366

Crumley CL (1994) Historical ecology: cultural knowledge and changing landscapes, School of American Research Press, Santa Fe

Daniels P (2014) Shellfish and resource sustainability on the Central Northwest Coast of North America. In: Roksandic M et al. (eds)The Cultural Dynamics of Shell-matrix Sites, Albuquerque, 223-240

Deur D (1999) Salmon, sedentism, and cultivation: toward an environmental prehistory of the Northwest Coast. In: Goble DD and Hirt P (eds) Northwest lands, Northwest peoples: Readings in Environmental History, University of Washington Press, Seattle, pp129-155

Deur D (2002) Rethinking Precolonial Plant Cultivation on the Northwest Coast of North America. Prof. Geogr. 54(2):140-157 https://doi.org/10.1111/0033-0124.00322

Deur D, Dick A, Recalma-Clutesi K, Turner NJ (2015) Kwakwaka'wakw "clam gardens". Hum. Ecol. 43(2):201-212

Deur D, Turner NJ (2005) Reconstructing Indigenous resource management, reconstructing the history of an idea. In: Deur D and Turner NJ (eds) Keeping it living University of Washington Press, Seattle

Deur DE (2000) A Domesticated Landscape: Native American Plant Cultivation on the Northwest Coast of North America. PhD Disseration, Department of Geography and Anthroplogy, Louisiana State University

DFO (2001) West Coast Vancouver Island sport fishery creel survey statistics 2001 and historical data 1984-2000 / by DM Lewis. Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo

DFO (2015) West Coast Vancouver Island Test Seine Samples Sections: 231, 232, 233, 1975-2010. Department of Fisheries and Oceans, Pacific Biological Station, Nanaimo

DFO (2022) Intertidal Clam: Pacific Region. In: Fisheries and Oceans Canada. https://www.pac.dfo-mpo.gc.ca/fm-gp/commercial/shellfish-mollusques/clam-palourde/index-eng.html

Duarte CM, et al. (2020) Rebuilding marine life. Nature 580(7801):39-51 https://doi.org/10.1038/s41586-020-2146-7

Efford MK (2019) Ts’a7inwa (gooseneck barnacles) as a proxy for archaeological efforts to understand shellfish as food in Nuu-chah-nulth territories. MA Thesis, University of Victoria, Victoria

Ellis DW, Swan LF (1981) Teachings of the Tides: Uses of Marine Invertebrates by the Manhousat People. Theytus Books, Nanaimo

Ellis DW, Wilson SB (1981) The Knowledge and Usage of Marine Invertebrates by the Skidegate Haida People of the Queen Charlotte Islands, Queen Charlotte Islands Museum Society

Erlandson JM (1988) The Role of Shellfish in Prehistoric Economies: A Protein Perspective. Am. Antiq. 53(1):102-109 https://doi.org/10.2307/281156

Erlandson JM (2001) The Archaeology of Aquatic Adaptations: Paradigms for a New Millennium. J. Archaeol. Res. 9(4):287-350 https://doi.org/10.1023/A:1013062712695

Erlandson JM, Rick TC (2010) Archaeology meets marine ecology: the antiquity of maritime cultures and human impacts on marine fisheries and ecosystems. Annu. Rev. Mar. Sci. 2:231-251

Fedje DW, Mackie AP, Wigen RJ, Mackie Q, Lake C (2005) Kilgii Gwaay: An early maritime site in the south of Haida Gwaii. In: Fedje DW and Mathewes RW (eds) Haida Gwaii:

Human history and environment from the Time of Loon to the Time of the Iron People. UBC Press, Vancouver, pp187-203

Finney BP, Gregory-Eaves I, Douglas MSV, Smol JP (2002) Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years. Nature 416(6882):729-733 https://doi.org/10.1038/416729a

Folke C, Colding J, Berkes F (2002) Synthesis: building resilience and adaptive capacity in social–ecological systems. In: Berkes F, Colding J, Folke C (eds) Navigating Social-Ecological Systems: Building Resilience for Complexity and Change. Cambridge University Press, Cambridge, p 352-387

Fossile T, Ferreira J, da Rocha Bandeira D, Figuti L, Dias-da-Silva S, Hausmann N, Robson HK, Orton D, Colonese AC (2019) Pre-Columbian fisheries catch reconstruction for a subtropical estuary in South America. Fish and Fisheries 20(6):1124-1137

Foster E (2021) Sea otter effects on soft-sediment flora and fauna, and within ancient Indigenous maricultural systems. PhD Dissertation, University of Victoria, Victoria

Foster E, Watson J, Lemay MA, Tinker MT, Estes JA, Piercey R, Henson L, Ritland C, Miscampbell A, Nichol L, Hessing-Lewis M, Salomon AK, Darimont CT (2021) Physical disturbance by recovering sea otter populations increases eelgrass genetic diversity. Science 374(6565):333-336 https://doi.org/10.1126/science.abf2343

Friele PA, Hutchinson I (1993) Holocene sea-level change on the central west coast of Vancouver Island, British Columbia. Can. J. Earth Sci. 30(4):832-840 https://doi.org/10.1139/e93-069

Froese R, Pauly D (2021) FishBase. In. https://fishbase.mnhn.fr/search.php

Fuentes A (2016) The extended evolutionary synthesis, ethnography, and the human niche: Toward an integrated anthropology. Curr. Anthropol. 57(13):13-26

Gifford-Gonzalez DP (2018) An Introduction to Zooarchaeology. Springer, New York

Giovas CM (2009) The shell game: analytic problems in archaeological mollusc quantification. J. Archaeol. Sci. 36(7):1557-1564 https://doi.org/10.1016/j.jas.2009.03.017

Golden CD, et al. (2016) Nutrition: Fall in fish catch threatens human health. Nature 534(7607):317-320 https://doi.org/10.1038/534317a

Gregr EJ, Christensen V, Nichol L, Martone RG, Markel RW, Watson JC, Harley CDG, Pakhomov EA, Shurin JB, Chan KMA (2020) Cascading social-ecological costs and benefits triggered by a recovering keystone predator. Science 368(6496):1243-1247 https://doi.org/10.1126/science.aay5342

Grier C, Angelbeck B, McLay E (2017) Terraforming and moumentality as long-term social ractice in the Salish Sea region of the Northwest Coast of North America. Hunt. Gatherer Res. 3(1):107-132 https://doi.org/10.3828/hgr.2017.2

Groesbeck AS, Rowell K, Lepofsky D, Salomon AK (2014) Ancient clam gardens increased shellfish production: adaptive strategies from the past can inform food security today. PloS One 9(3):e91235-e91235 https://doi.org/10.1371/journal.pone.0091235

Grone MA (2020) Of molluscs and middens: Historical ecology of indigenous shoreline stewardship along the central coast of California. PhD Dissertation, Department of Anthropology, University of California Press, Berkeley.

Gunter E (1926) An Analysis of the First Salmon Ceremony. Am. Anthropol. 28(4):605-617

Haggan N, Turner N, Carpenter J, Jones JT, Mackie Q, Menzies C (2006) 12,000+ years of change: linking traditional and modern ecosystem science in the Pacific Northwest. Fisheries Centre, University of British Columbia, Vancouver

Hambrecht G, Anderung C, Brewington S, Dugmore A, Edvardsson R, Feeley F, Gibbons K, Harrison R, Hicks M, Jackson R (2018) Archaeological sites as distributed long-term observing networks of the past (DONOP). Quat. Int. https://doi.org/10.1016/j.quaint.2018.04.016

Harris C (2004) How Did Colonialism Dispossess? Comments from an Edge of Empire. Ann. Assoc. Am. Geogr. 94(1):165-182 https://doi.org/10.1111/j.1467-8306.2004.09401009.x

Harris DC (2009) Landing Native fisheries: Indian reserves and fishing rights in British Columbia, 1849-1925. UBC Press, Vancouver

Hillis D, McKechnie I, Guiry E, Claire DES, Darimont CT (2020) Ancient dog diets on the Pacific Northwest Coast: zooarchaeological and stable isotope modelling evidence from Tseshaht territory and beyond. Sci. Rep. 10(1):1-12

Hoffmann T, Lyons N, Miller D, Diaz A, Homan A, Huddlestan S, Leon R (2016) Engineered feature used to enhance gardening at a 3800-year-old site on the Pacific Northwest Coast. Sci. Adv. 2(12):e1601282-e1601282 https://doi.org/10.1126/sciadv.1601282

Holling CS (1973) Resilience and stability of ecological systems. Ann. Rev. Ecol. Syst. 4(1):1-23

Holling CS, Gunderson LH (2002) Panarchy: understanding transformations in human and natural systems. Island Press, Washington, DC

Huber HR, Jorgensen JC, Butler VL, Baker G, Stevens R (2011) Can salmonids (*Oncorhynchus* spp.) be identified to species using vertebral morphometrics? J. Archaeol. Sci. 38(1):136-146

Ingold T (1993) The temporality of the landscape. World Archaeol. 25(2):152-174 https://doi.org/10.1080/00438243.1993.9980235

Jackley J, Gardner L, Djunaedi AF, Salomon AK (2016) Ancient clam gardens, traditional management portfolios, and the resilience of coupled human-ocean systems. Ecol. Soc. 21(4) https://doi.org/10.5751/ES-08747-210420

Jackson JB (2001) What was natural in the coastal oceans? PNAS 98(10):5411-5418

Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, Estes J, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ, Warner RR (2001) Historical Overfishing and the Recent Collapse of Coastal Ecosystems. Science 293(5530):629-637 https://doi.org/10.1126/science.1059199

Kittinger JN, McClenachan L, Gedan KB, Blight LK (eds) (2015) Marine historical ecology in conservation: applying the past to manage for the future, University of California Press, Oakland.

Klein RG, et al. (2004) The Ysterfontein 1 Middle Stone Age site, South Africa, and early human exploitation of coastal resources. PNAS 101(16):5708-5715

Kvitek RG, Oliver J, DeGange A, Anderson B (1992) Changes in Alaskan soft-bottom prey communities along a gradient in sea otter predation. Ecol. 73(2):413-428

Langdon SJ (2006) Selective Traditional Tlingit Salmon Fishing Techniques on the West Coast of the Prince of Wales Archipelago. In: Menzies C (ed) Traditional ecological knowledge and natural resource management. University of Nebraska Press, Lincon

Lepofsky D, Smith NF, Cardinal N, Harper J, Morris M, Gitla EW, Bouchard R, Kennedy DID, Salomon AK, Puckett M, McLay E (2015) Ancient shellfish mariculture on the Northwest Coast of North America. Am. Antiq. 80(2):236-259

Letham B, Martindale A, Ames KM (2020) Endowment, investment, and the transforming coast: Long-term human-environment interactions and territorial proprietorship in the Prince Rupert Harbour, Canada. J. Anthropol. Archaeol. 59:101179

Lotze H, McClenachan L (2013) Marine historical ecology: informing the future by learning from the past. In: Bertness MD et al. (eds) Marine Community Ecology and Conservation, Sinauer, pp 165-200

Lyons N, Hoffmann T, Miller D, Martindale A, Ames KM, Blake M (2021) Were the Ancient Coast Salish Farmers? A Story of Origins. Am. Antiq. 86(3):504-525

Maire E, Graham NAJ, MacNeil AM, Lam VWY, Robinson JPW, Cheung WWL, Hicks CC (2021) Micronutrient supply from global marine fisheries under climate change and overfishing. Curr. Biol. 31(18):4132-4138

Marean CW, Bar-Mathews M, Bematchez J, Fisher E, Goldberg P, Herries AIR, Jacobs Z, Jerardino A, Karkanas P, Minichillo T(2007) Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. Nature 449(7164):905-908

Markel RW, Shurin JB (2015) Indirect effects of sea otters on rockfish (*Sebastes* spp.) in giant kelp forests. Ecol. 96(11):2877-2890

Maschner H, Finney B, Jordan J, Misarti N, Tews A, Knudsen G (2009) Did the North Pacific ecosystem collapse in AD 1250? In: Maschner H, Manson OK, McGhee R (eds) The Northern World, AD 900-1400, University of Utah Press, Salt Lake City

Mathews DL, Turner NJ (2017) Ocean cultures: Northwest Coast ecosystems and indigenous management systems. In: Levin PS and Poe MR (eds) Conservation for the Anthropocene Ocean, Academic Press, pp 169-206

McClenachan L, Ferretti F, Baum JK (2012) From archives to conservation: why historical data are needed to set baselines for marine animals and ecosystems. Conserv. Lett. 5(5):349-359 https://doi.org/10.1111/j.1755-263X.2012.00253.x

McClenachan L, Grabowski JH, Marra M, McKeon CS, Neal BP, Record NR, Scyphers SB (2019) Shifting perceptions of rapid temperature changes' effects on marine fisheries, 1945–2017. Fish and Fisheries 20(6):1111-1123 https://doi.org/10.1111/faf.12400

McKechnie I (2005a) Column Sampling and the Archaeology of Small Fish at Ts'ishaa. In: McMillan A and St. Claire D (eds) Ts'ishaa: Archaeology and Ethnography of a Nuu-chah-nulth Origin Site in Barkley Sound, Archaeology Press, Simon Fraser University, Burnaby, pp 206-223

McKechnie I (2005b) Five thousand years of fishing at a shell midden in the Broken Group Islands, Barkley Sound, British Columbia. MA Thesis, Department of Archaeology, Simon Fraser University, Burnaby.

McKechnie I (2007a) Investigating the complexities of sustainable fishing at a prehistoric village on western Vancouver Island, British Columbia, Canada. J. Nat. Conserv. 15(3):208-222

McKechnie I (2007b) Vertebrate faunal analysis at Himayis (205T, DeSi-17) and the Clarke Island Defensive Site (212T, DeSi-26), Broken Group Islands, Pacific Rim National Park Reserve. Parks Canada, Cultural Resource Services, Victoria, pp 1-68

McKechnie I (2012) Zooarchaeological Analysis of the Indigenous Fishery at the Huu7ii Big House and Back Terrace, Huu-ay-aht Territory, Southwestern Vancouver Island. In: McMillan AD and St. Claire DE (eds) Huu7ii: Household Archaeology at a Nuu-chah-nulth Village Site in Barkley Sound, Archaeology Press, Simon Fraser University, Burnaby, pp 154-186

McKechnie I (2014) An archaeology of food and settlement on the Northwest Coast. PhD Dissertation, Department of Anthropology, University of British Columbia, Vancouver

McKechnie I (2015) Indigenous oral history and settlement archaeology in Barkley Sound, Western Vancouver Island. BC Studies (187):193-228

McKechnie I, Lepofsky D, Moss ML, Butler VL, Orchard TJ, Coupland G, Foster F, Caldwell M, Lertzman K (2014) Archaeological data provide alternative hypotheses on Pacific herring (*Clupea pallasii*) distribution, abundance, and variability. PNAS 111(9):E807-E816 https://doi.org/10.1073/pnas.1316072111

McKechnie I, Moss ML (2016) Meta-analysis in zooarchaeology expands perspectives on Indigenous fisheries of the Northwest Coast of North America. J. Archaeol. Sci. 8:470-485 https://doi.org/10.1016/j.jasrep.2016.04.006

McKechnie I, St Claire D (n.d.) Keith Island Archaeological Project interm field report for 2021: Report to be submitted to Tseshaht First Nation and Pacific Rim National Park Reserve

McKechnie I, Wigen RJ (2011) Toward a Historical Ecology of Pinniped and Sea Otter Hunting Traditions on the Coast of Southern British Columbia. In: Braje TJ and Rick TC (eds)

Human Impacts on Seals, Sea Lions, and Sea Otters: Integrating Archaeology and Ecology in the Northeast Pacific, University of California Press, Berkeley

McKenzie K (2021) University of Victoria - Zooarchaeology Lab Collection v1.1. University of Victoria, Victoria, https://doi.org/10.5886/jej09d

McMillan AD, McKechnie I, St. Claire DE, Frederick SG (2008) Exploring variability in maritime resource use on the Northwest Coast: A case study from Barkley Sound, Western Vancouver Island. Canadian Journal of Archaeology:214-238

McMillan AD, St. Claire DE (2005) Ts'ishaa: Archaeology and Ethnography of a Nuu-chah-nulth Origin Site in Barkley Sound. Archaeology Press, Simon Fraser University, Burnaby.

McMillan AD, St. Claire DE (2012) Huu7ii: household archaeology at a Nuu-chah-nulth Village site in Barkley Sound. Archaeology Press, Simon Fraser University, Burnaby.

Menzies CR (ed) (2006) Traditional ecological knowledge and natural resource management. University of Nebraska Press, Lincon.

Menzies CR, Butler CF (2007) Returning to Selective Fishing through Indigenous Fisheries Knowledge: The Example of K'moda, Gitxaała Territory. Am. Indian Q. 31(3):441-464

Mills LS, Soulé ME, Doak DF (1993) The keystone-species concept in ecology and conservation. J. Biosci. 43(4):219-224

Miszaniec JI (2021) Assessing past ecological tolerance of Pacific salmon (*Oncorhynchus* spp.) and saffron cod (*Eleginus gracilis*) in northwest Alaska using vertebra width and length reconstructions. Archaeol. Anthropol.Sci. 13(6):1-14

Monks GG (2003) The Cultural Taphonomy of Nuu-chah-nulth Whale Bone Assemblages. In: Matson RG, Coupland G, and Mackie Q (eds) Emerging from the Mist: Studies in Northwest Coast Culture History, UBC Press, Vancouver, pp 188-212

Monks GG (2017) Evidence of Changing Climate and Subsistence Strategies Among the Nuu-chah-nulth of Canada's West Coast. In: Monks GG (ed) Climate Change and Human Responses: A Zooarchaeological Perspective. Springer, Dordrecht, pp 173-196

Monks GG, McMillan AD, St. Claire DE (2001) Nuu-Chah-Nulth whaling: archaeological insights into antiquity, species preferences, and cultural importance. Arct. Anthropol.:60-81

Moss ML (1993) Shellfish, gender, and status on the Northwest Coast: Reconciling archeological, ethnographic, and ethnohistorical records of the Tlingit. Am. Anthropol. 95(3):631-652

Moss ML (2011) Northwest Coast: Archaeology as Deep History. SAA Press, Washington, D.C.

Moss ML (2012) Understanding Variability in Northwest Coast Faunal Assemblages: Beyond Economic Intensification and Cultural Complexity. J. Isl. Coast. Archaeol. 7(1):1-22 https://doi.org/10.1080/15564894.2011.586090

Moss ML, Cannon A (eds) (2011) The Archaeology of North Pacific Fisheries. University of Alaska Press, Fairbanks

Moss ML, Judd KG, Kemp BM (2014) Can salmonids (*Oncorhynchus* spp.) be identified to species using vertebral morphometrics? A test using ancient DNA from Coffman Cove, Alaska. J. Archaeol. Sci. 41:879-889

Moss ML, Yang DY, Newsome SD, Speller CF, McKechnie I, McMillan AD, Losey RJ, Koch P (2006) Historical Ecology and Biogeography of North Pacific Pinnipeds: Isotopes and

Ancient DNA from Three Archaeological Assemblages. J. Isl. Coast. Archaeol. 1(2):165-190

Newsome SD, Etnier MA, Gifford-Gonzalez D, Phillips DL, van Tuinen M, Hadly EA, Costa DP, Kennett DJ, Guilderson TP, Koch PL (2007) The Shifting Baseline of Northern Fur Seal Ecology in the Northeast Pacific Ocean. PNAS 104(23):9709-9714 https://doi.org/10.1073/pnas.0610986104

Ng J, Cheung WWL (2022) Signature of climate-induced changes in seafood species served in restaurants. Environ. Biol. Fishes. https://doi.org/10. 1007/s10641-022-01244-6

Nims R, Butler VL (2019) The sablefish (*Anoplopoma fimbria*) of Čï̓xwicən: Socioenvironmental lessons from an unusually abundant species. Journal of Archaeol.Sci. Rep. 23:1187-1196 https://doi.org/10.1016/j.jasrep.2018.06.028

Norgaard RB (2006) Development betrayed: The end of progress and a co-evolutionary revisioning of the future. Routledge, London

NPAFC (2021) NPAFC Pacific salmonid catch statistics (updated September 2021). North Pacific Anadromous Fish Commission, Vancouver.

O’Connell JM, Tunnicliffe V (2001) The use of sedimentary fish remains for interpretation of long-term fish population fluctuations. Mar. Geol. 174(1-4):177-195 https://doi.org/10.1016/S0025-3227(00)00149-3

O’Connor S, Ono R, Clarkson C (2011) Pelagic fishing at 42,000 years before the present and the maritime skills of modern humans. Science 334(6059):1117-1121

Onat AB (1985) The multifunctional use of shellfish remains: from garbage to community engineering. Northwest Anthroplogical Research Notes 19(1):201-207

Orchard TJ (2003) An application of the linear regression technique for determining length and weight of six fish taxa: The role of selected fish species in Aleut paleodiet. Vol 1172. British Archaeological Reports, Oxford.

Orchard TJ, Clark T (2005) Multidimensional Scaling of Northwest Coast Faunal Assemblages: A Case Study from Southern Haida Gwaii, British Columbia. Canadian Journal of Archaeology 29(2):88-112

Orchard TJ, Szpak P (2011) Identification of salmon species from archaeological remains on the Northwest Coast. In: Moss ML and Cannon A (eds) The Archaeology of North Pacific Fisheries. University of Alaska Press, Fairbanks, pp 17-29

Pauly D (1995) Anecdotes and the shifting baseline syndrome of fisheries. Trends Ecol. 10(10):430-430 https://doi.org/10.1016/s0169-5347(00)89171-5

Pinkerton E, Salomon AK, Dragon F (2019) Reconciling social justice and ecosystem-based management in the wake of a successful predator reintroduction. Can. J. Fish. Aquat. Sci. 76(6):1031-1039 https://doi.org/10.1139/cjfas-2018-0441

Pinsky ML, Worm B, Fogarty MJ, Sarmiento JL, Levin SA (2013) Marine Taxa Track Local Climate Velocities. Science 341(6151):1239-1242 https://doi.org/10.1126/science.1239352

Poertner HO, Knust R (2007) Climate Change Affects Marine Fishes through the Oxygen Limitation of Thermal Tolerance. Science 315(5808):95-97 https://doi.org/10.1126/science.1135471

Praetorius SK, Mix AC, Walczak MH, Wolhowe MD, Addison JA, Prahl FG (2015) North Pacific deglacial hypoxic events linked to abrupt ocean warming. Nature 527(7578):362-366 https://doi.org/10.1038/nature15753

Ramsey BC (2009) Bayesian Analysis of Radiocarbon Dates. Radiocarbon 51(1):337-360 https://doi.org/10.1017/S0033822200033865

Reimer PJ, et al. (2020) The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP). Radiocarbon 62(4):725-757 https://doi.org/10.1017/RDC.2020.41

Reisewitz SE, Estes JA, Simenstad CA (2006) Indirect food web interactions: sea otters and kelp forest fishes in the Aleutian archipelago. Oecologia 146(4):623-631

Rodrigues AT, McKechnie I, Yang DY (2018) Ancient DNA analysis of Indigenous rockfish use on the Pacific Coast: Implications for marine conservation areas and fisheries management. PloS One 13(2):e0192716-e0192716

R.S.C. (1985) Fisheries Act RSC., F-14, s 1. https://laws.justice.gc.ca/eng/acts/f-14/index.html

Salmen-Hartley JU (2018) Towards a historical ecology of halibut fishing on the Northwest Coast. MA Thesis, Department of Anthropology, University of Victoria, Victoria

Salomon AK, Burt JM, Kii’iljuus Barb JW, McKechnie I (2020) Coastal Voices: Lessons Learned and Recommendations on Revitalizing Our Relationship with Sea Otters, Kelp Forests and Coastal Fisheries. Simon Fraser University, School of Resource and Environmental Management, Burnaby

Salomon AK, Kii’iljuus Barb JW, White XE, Tanape Sr N, Happynook TM (2015) First Nations perspectives on sea otter conservation in British Columbia and Alaska: insights into coupled human–ocean systems. In: Larson S et al. (eds) Sea Otter Conservation. Elsevier, New York, pp 301-331

Salomon AK, Lertzman K, Brown K, Wilson K̲iB, Secord D, McKechnie I (2018) Democratizing conservation science and practice. Ecology and Society 23(1):44 https://doi.org/10.5751/ES-09980-230144

Salomon AK, Quinlan AE, Pang GH, Okamoto DK, Vazquez-Vera L (2019) Measuring social-ecological resilience reveals opportunities for transforming environmental governance. Ecology and Society 24(3):16 https://doi.org/10.5751/ES-11044-240316

Sanchez GM (2020) Indigenous stewardship of marine and estuarine fisheries?: Reconstructing the ancient size of Pacific herring through linear regression models. J. Archaeol. Sci. Rep. 29:102061 https://doi.org/10.1016/j.jasrep.2019.102061

Sandweiss DH (2003) Terminal Pleistocene through Mid-Holocene archaeological sites as paleoclimatic archives for the Peruvian coast. Palaeogeogr. Palaeoclimatol. Palaeoecol. 194(1-3):23-40 https://doi.org/10.1016/s0031-0182(03)00270-0

Singh GG, Markel RW, Martone RG, Salomon AK, Harley CDG, Chan KMA (2013) Sea otters homogenize mussel beds and reduce habitat provisioning in a rocky intertidal ecosystem. PloS One 8(5):e65435-e65435 https://doi.org/10.1371/journal.pone.0065435

Singh GG, McKechnie I (2015) Making the most of fragments: a method for estimating shell length from fragmentary mussels (*Mytilus californianus* and *Mytilus trossulus*) on the Pacific Coast of North America. J. Archaeol. Sci. 58:175-183

Singh GG, McKechnie I, Braje TJ, Campbell B (2015) “All models are wrong but some are useful”: A response to Campbell's comment on estimating *Mytilus californianus* shell size. J. Archaeol. Sci. 63:160-163 https://doi.org/10.1016/j.jas.2015.08.021

Slade E, McKechnie I, Salomon AK (2022) Archaeological and Contemporary Evidence Indicates Low Sea Otter Prevalence on the Pacific Northwest Coast During the Late Holocene. Ecosystems 25:548-566

Smith NF, McKechnie I, St Claire D (2012) K̲ak̲mak̲imilh - Keith Island Wharf and Gazebo Installation: An Archaeological Impact Assessment. Report Prepared for Tseshaht First Nation and Pacific Rim Park Reserve of Canada

Soutar A, Isaacs JD (1969) History of fish populations inferred from fish scales in anaerobic sediments off California. Cal. COFI Rep. 13:63-70

St Claire D (1991) Barkley Sound Tribal Territories. In: Arima E, St Claire D, Clamhouse L, Edgar J, Jones C, Thomas J (eds) Between Ports Alberni and Renfrew: Notes on West Coast Peoples. Canadian Ethnology Service, Canadian Museum of Civilization, Ottawa, Ontario, pp 13-202

Steneck RS, Pauly D (2019) Fishing through the Anthropocene. Curr. Biol. 29(19):R987-R992 https://doi.org/10.1016/j.cub.2019.07.081

Stringer CB, Finlayson JC, Barton RNE, Fernández-Jalvo Y, Cáceres I, Sabin RC, Rhodes EJ, Currant AP, Rodríguez-Vidal J, Giles-Pacheco F (2008) Neanderthal exploitation of marine mammals in Gibraltar. PNAS 105(38):14319-14324

Sumpter ID (2005) An analysis of three shellfish assemblages from Ts' ishaa, site DfSi-16 (204T), Benson Island, Pacific Rim National Park Reserve. In: McMillan A and St. Claire D (eds) Ts' ishaa: Archaeology and Ethnography of a Nuu-chah-nulth Origin Site in Barkley Sound. Archaeology Press, Simon Fraser University, Burnaby

Sundstrom SM, Allen CR (2019) The adaptive cycle: More than a metaphor. Ecol. Complex. 39:100767 https://doi.org/10.1016/j.ecocom.2019.100767

Thakar HB (2011) Intensification of shellfish exploitation: evidence of species-specific deviation from traditional expectations. J. Archaeol. Sci. 38(10):2596-2605 https://doi.org/10.1016/j.jas.2011.05.008

Thakar HB, Glassow MA, Blanchette CA (2017) Reconsidering evidence of human impacts: Implications of within-site variation in growth rates in *Mytilus californianus* along tidal gradients. Quat. 427(1):151-159 https://doi.org/10.1016/j.quaint.2015.10.018

Thornton TF (1999) Tleikwaani, the “Berried Landscape”, the Structure of Tlingit Edible Fruit Resources at Glacier Bay, Alaska. J. Ethnobiol. 19(1):27-48

Thornton TF, Moss ML, Butler VL, Hebert J, Funk F (2010) Local and Traditional Knowledge and the Historical Ecology of Pacific Herring in Alaska. J. Ecol. Anthropol. 14(1):81-88

Todd Z (2018) Refracting the state through human-fish relations: Fishing, indigenous legal orders and colonialism in north/western Canada. Decolonization: Indigeneity, Education & Society 7(1):60-75

Toniello G, Lepofsky D, Lertzman-Lepofsky G, Salomon AK, Rowell K (2019) 11,500 y of human–clam relationships provide long-term context for intertidal management in the Salish Sea, British Columbia. PNAS 116(44):22106-22114 https://doi.org/10.1073/pnas.1905921116

Tunnicliffe V, O’Connell JM, McQuoid MR (2001) A Holocene record of marine fish remains from the Northeastern Pacific. Mar. Geol. 174(1-4):197-210 https://doi.org/10.1016/S0025-3227(00)00150-X

Turner NJ, Wilson B (2008) The culture of forests: Haida traditional knowledge and forestry in the 21st century. Wild Foresting: Practicing Nature's Wisdom Island Press, Washington, DC:130-137

Turner NJ (1999) Time to burn: traditional use of fire to enhance resource production by Aboriginal Peoples in British Columbia. In: Boyd R (ed) Indians, fire and the land in the Pacific Northwest. Oregon State University Press, Corvallis:185-218

Turner NJ (2008) The earth’s blanket: Traditional teachings for sustainable living. University of Washington Press, Seattle

Turner NJ, Clifton H (2006) The forest and the seaweed: Gitga’at seaweed, traditional ecological knowledge and community survival. In: Pieroni A and Price L (eds) Eating and healing: traditional food as medicine. Routledge:153-179

Turner NJ, Peacock S (2005) Solving the perennial paradox: ethnobotanical evidence for plant resource management on the Northwest Coast. In: Deur DE and Turner NJ (eds) Keeping it living: traditions of plant use and cultivation on the Northwest Coast of North America. University of Washington Press:101-50

Vigneron M (2021) Estimating Pile Perch (*Rhacochilus vacca*) Size at K̲ak̲mak̲imilh (306T): Potential Evidence for Stone Walled Tidal Fish Trap Use By Inhabitants of Kakmakimilh. A report on file, K̲ak̲mak̲imilh Archaeological Project, University of Victoria, Victoria

Walker B, Hollin CS, Carpenter, Kinzig A (2004) Resilience, Adaptability and Transformability in Social–ecological Systems. Ecol. 9(2):5 https://doi.org/10.5751/ES-00650-090205

Weatherdon LV, Ota Y, Jones MC, Close DA, Cheung WWL (2016) Projected Scenarios for Coastal First Nations' Fisheries Catch Potential under Climate Change: Management Challenges and Opportunities. PloS One 11(1):e0145285-e0145285 https://doi.org/10.1371/journal.pone.0145285

Whitaker AR (2008) Incipient aquaculture in prehistoric California?: Long-term productivity and sustainability vs. immediate returns for the harvest of marine invertebrates. J. Archaeol. Sci. 35(4):1114-1123 https://doi.org/10.1016/j.jas.2007.08.005

Wilson TJB, Cooley SR, Tai TC, Cheung WWL, Tyedmers PH (2020) Potential socioeconomic impacts from ocean acidification and climate change effects on Atlantic Canadian fisheries. PloS One 15(1):e0226544-e0226544 https://doi.org/10.1371/journal.pone.0226544

Wright CA, Dallimore A, Thomson RE, Patterson RT, Ware DM (2005) Late Holocene paleofish populations in Effingham Inlet, British Columbia, Canada. Palaeogeogr. Palaeoclimatol. Palaeoecol. 224(4):367-384 https://doi.org/10.1016/j.palaeo.2005.03.041

Yanai RD, Battles JJ, Richardson AD, Blodgett CA, Wood DM, Rastetter EB (2010) Estimating Uncertainty in Ecosystem Budget Calculations. Ecosystems 13(2):239-248 https://doi.org/10.1007/s10021-010-9315-8

Zeder MA (2018) Why evolutionary biology needs anthropology: evaluating core assumptions of the extended evolutionary synthesis. Evol. Anthropol. 27(6):267-284